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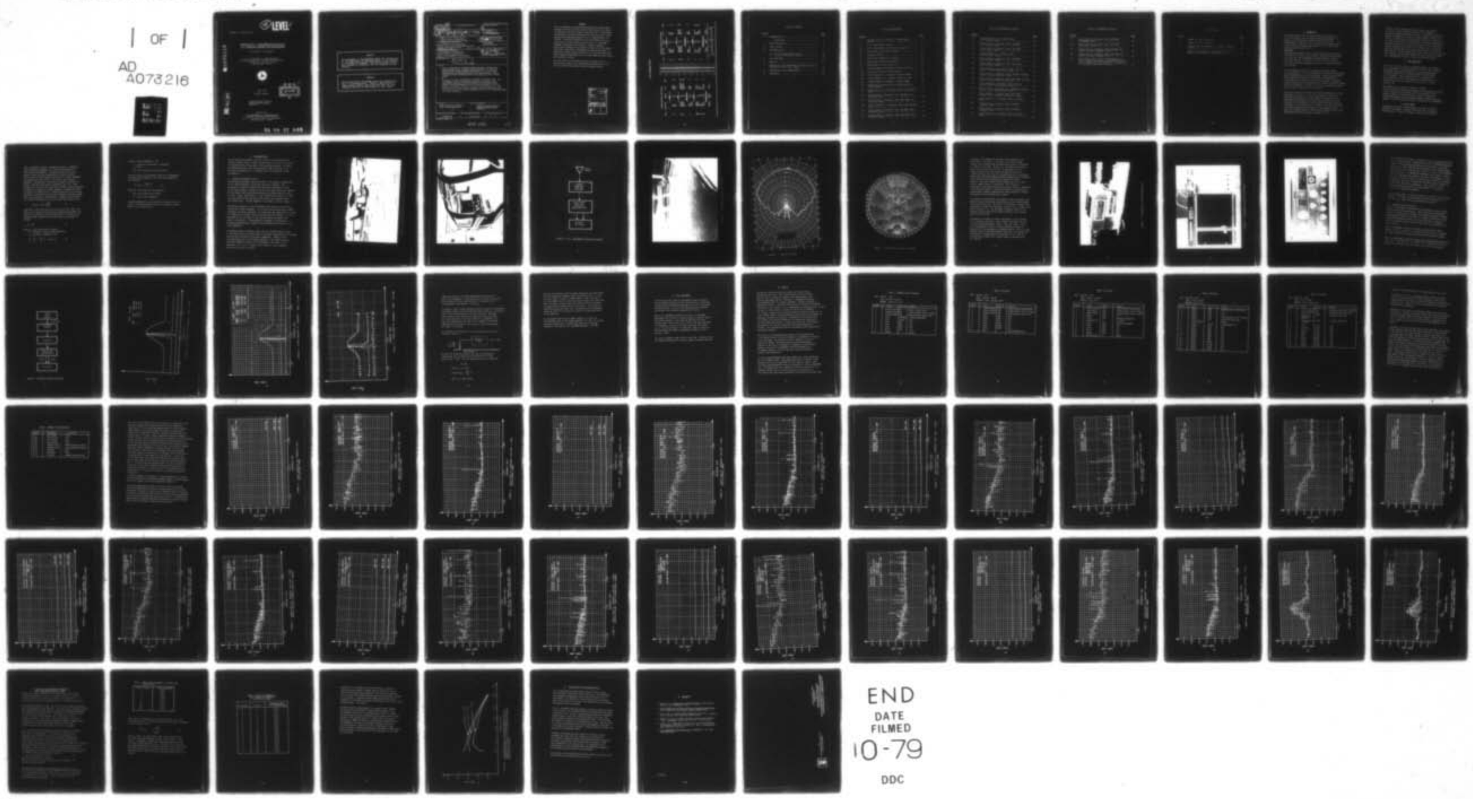

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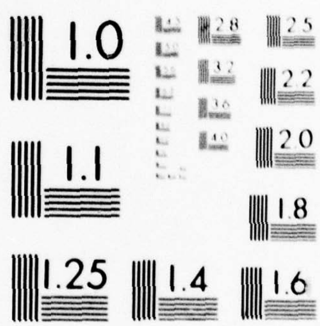

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REPORT NO. FAA-EM-79-10

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RESULTS OF R.F.I. MEASUREMENTS MADE IN THE G.P.S. BAND ON A GENERAL AVIATION AIRCRAFT

Christopher B. Duncombe

U.S. DEPARTMENT OF TRANSPORTATION
RESEARCH AND SPECIAL PROGRAMS ADMINISTRATION
Transportation Systems Center
Cambridge MA 02142

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Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Office of Systems Engineering Management
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TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Access on No.	3. Recipient's Catalog No.
18 19 FAA-EM-79-10		11

4. Title and Subtitle	5. Report Date
6 Results of R.F.I. Measurements Made in the G.P.S. Band on a General Aviation Aircraft	June 1979
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
10 Christopher B. Duncombe	14 [redacted]TSC-FAA-79-10

9. Performing Organization Name and Address	10. Work Unit No.
U.S. Department of Transportation Research and Special Programs Administration Transportation Systems Center Cambridge MA 02142 407 082	FA957/R9138
	11. Contract or Grant No.
	13. Type of Report and Period Covered

12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
U.S. Department of Transportation Federal Aviation Administration Office of Systems Engineering Management Washington DC 20591	9 Interim Report, Sept 78 - June 79
	14. Sponsoring Agency Code

15. Supplementary Notes

12 75 p'

16. Abstract

The U.S. Department of Transportation/Transportation Systems Center performed tests aboard a General Aviation aircraft in an effort to characterize the radio frequency interference (R.F.I.) environment, encountered by the receiving system of this type aircraft, in the Navstar Global Positioning System (G.P.S.) L_1 frequency band, 1575 MHz $\pm$ 10MHz.

L sub 1

+ or -

Results of the R.F.I. measurements, performed in the Boston, Mass. area in December of 1978, are presented along with an analysis of the interference potential of the third harmonic of television station Channel 23 to the performance of a G.P.S. receiver designed to operate on the L_1 C/A signal. The results show that no significant R.F.I. was observed in the L_1 band of the G.P.S. which leads to the conclusion that R.F.I. should not pose a serious limitation to low cost G.P.S. receiver design for General Aviation.

17. Key Words	18. Distribution Statement
Radio Frequency Interference, Global Positioning System	DOCUMENT IS AVAILABLE TO THE PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	76	

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PREFACE

The U.S. Department of Transportation/Transportation Systems Center performed tests aboard a General Aviation (GA) aircraft in an effort to characterize the radio frequency interference (R.F.I.) environment, encountered by the receiving system of this type of aircraft, in the Navstar Global Positioning System (G.P.S.) L_1 frequency band, 1575 ± 10 MHz. A microstrip crossed-slot antenna was mounted on the top center-line of a Piper Cherokee Arrow III and R.F.I. measurement equipment rack mounted in the aircraft. Graphs of received power versus frequency were recorded while the aircraft flew numerous diversified flight paths. Measurements were made day and night, on ground and in flight (various altitudes), over rural and urban areas, while climbing and descending, and at a large commercial airport and at small municipal airports.

The author wishes to acknowledge the help and support of Leslie Klein and Peter Engels of the Transportation Systems Center as well as that of Robert Pipes and Mark Aalyson of Wiggins Airways.

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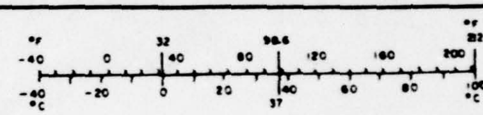
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. INTRODUCTION

This document reports on a brief measurement program carried out by TSC for the FAA's Office of Systems Engineering Management. The purpose of this program was to measure and characterize the radio-frequency interference (R.F.I.) environment of general aviation aircraft in the L_1 frequency band (centered at 1575.42 MHz) of the Global Positioning System (G.P.S.).

BACKGROUND

This measurement program is one of several tasks being carried out by TSC as part of the FAA's overall program of communications improvement for oceanic ATC, and investigation of the applicability of GPS to civil air navigation. Specifically, the R.F.I. task is in support of the FAA's activities examining the use of G.P.S by general aviation (G/A) aircraft.

One of the major activities of this program for general aviation is the development of a low cost prototype G.P.S receiver with performance capable of meeting G/A aircraft requirements. Extensive design studies have already been carried out, and confidence has been gained in a basic approach to a simple, practical low cost design. A detailed technical specification is being prepared for the next hardware-procurement phase of this program. The results of the R.F.I. measurements reported here will form an element of this specification.

There are two reasons for concern about possible degradation in receiver performance due to R.F.I. First, the L_1 frequency is located in a potentially troublesome R.F.I. band, subject to interference from broad-band noise from maritime and aeronautical satellites, from UHF radars and from third-harmonic spurious radiation from UHF television transmitters. The second reason for concern is that the full processing gain (interference rejection) inherent in the pseudo-noise (PN) coded G.P.S. waveform may not be realized from a design-to-cost receiver implementation meeting performance requirements of G/A.

In order to obtain preliminary results in time for incorporation in the FAA's receiver procurement specification a minimum test program was planned and carried out by TSC. A microstrip crossed-slot antenna, representative of low-cost conformal designs suitable for G/A aircraft, was installed on the dorsal center-line over the cabin area of a Piper Cherokee Arrow. This antenna has a broad nearly hemispherical pattern and has promise as a GPS aircraft antenna. Noise measuring and recording equipment was installed in the aircraft cabin. Flights were made over large and small cities, open countryside and over large and small airports. Circular holding patterns were flown so that the main lobe of the antenna would illuminate ground based noise sources with maximum gain. Approximately 20 hours of flight test data were obtained.

2. MAJOR CONCLUSION

This is only the first stage of a comprehensive multi-year program of R.F.I. measurements to be undertaken soon by the FAA. This continuing program will refine and lend confidence to the data reported here. The results show that for the tests performed in the New England area in December of 1978 no significant R.F.I. was observed in the L_1 band of the G.P.S., which leads to the conclusion that R.F.I. should not pose a serious limitation to low cost G.P.S. receiver design for G/A.

The remainder of this report is organized as follows:
Section 3 reviews the noise theory pertinent to the measurements; Sections 4 and 5 describe the instrumentation and test procedures followed. Section 6 presents the results obtained. Section 7 analyzes the interference potential of high-powered transmission from UHF television channels. Section 8 presents the report's conclusions and recommendations.

3. NOISE THEORY

The design of an aircraft receiver depends on a number of different parameters, for example: bandwidth, acquisition time, carrier power and noise power. The noise, in general, consists of the following

types: atmospheric, galactic, man-made and receiver. Atmospheric noise originates predominantly from lightning discharges and is frequency and time dependent. Statistical values may vary from season to season and from one geographical location to another. Galactic noise is noise originating outside of the earth's atmosphere, the largest source being the sun. This noise is also frequency dependent. Man-made noise is generated by automobile ignitions, arc welders, neon signs, high voltage transmission lines, etc. Urban man-made noise is greater than rural and this noise is usually broadband. In general, the greater the receiver bandwidth, the greater the noise. See Reference 1 and Reference 2. Receiver noise is due to the thermal vibrations of electrons in resistors and recombination processes taking place in the junctions of semiconductors. A measure of the noisiness of a receiver or amplifier is its noise figure (NF), defined to be:

$$N.F._{dB} = 10 \log \frac{S_i/N_i}{S_o/N_o} \qquad (1)$$

where S_i/N_i is the input signal to noise ratio and S_o/N_o that of the output. For a typical receiving system consisting of an antenna, preamplifier, and receiver, the noise power density at the input to the receiving system (preamplifier and receiver) may be calculated as follows:

$$N_o = KT_s \qquad (2)$$

Where N_o = noise power density (watts/Hz)
K = Boltzmann's constant (-198.6 dBm/Hz/°K)
T_s = system noise temperature (°K)

$$T_s = \frac{T_A}{L} + \frac{L-1}{L}\, T_o + (NF-1)\, T_o \qquad (3)$$

where T_A = antenna temperature (°K)

L = cable loss from antenna to preamplifier

T_o = 290°K

NF = noise figure of the receiving system.

The noise figure of the receiving system, NF, is predominantly determined by the preamplifier for a high gain preamplifier, but in general:

$$NF = NF_1 + \frac{(NF_2 - 1)}{G_1} \qquad (4)$$

where NF_1 = noise figure of the preamplifier

NF_2 = noise figure of the receiver

G_1 = gain of the preamplifier.

From these equations can be calculated the thermal noise of the system. Noise measured above this level is spurious, random or impulsive from external sources.

4. INSTRUMENTATION

The TSC leased from Wiggins Aircraft, located at Norwood Municipal Airport, Norwood, Mass., a Piper Cherokee Arrow III. This is a typical G/A aircraft with a single engine, four passenger capacity, low wing, and retractable gear. The TSC measurement system consisted of the aircraft rack-mounted R.F.I. equipment plus the calibration system. See Figure 1.

4.1 AIRCRAFT MEASUREMENT SYSTEM

The aircraft measurement system consisted of the antenna, preamplifier, R.F.I. receiver/analyzer, XY plotter and static inverter. The preamplifier, inverter, analyzer and plotter were mounted in a rack in the space normally occupied by the two rear seats; these were removed for the flight tests and reinstalled when the aircraft was not in use for R.F.I. tests. (See Figure 2). This allowed the aircraft to be used for other projects when not used for TSC tests and eliminated long term rental costs. A block diagram of the system is shown in Figure 3.

The aircraft antenna is a low-cost design which operates at the GPS L_1 (1575.42 MHz) signal frequency. It is a microstrip crossed-slot element, right-hand circularly polarized. Its dimensions are approximately 4 inches by 4 inches by one quarter inch with an attached SMA connector. It was installed in the top center of the aircraft behind the glide slope sensor. See Figure 4. This antenna was designed to provide good up-looking hemispherical coverage while providing good rejection in the lower hemisphere.

The antenna pattern of Figure 5 shows that the antenna provides three to four dB of gain over a wide angle in the upper hemisphere while providing about 20 dB of rejection in the lower hemisphere. Figure 6 shows the Smith Chart plot of the antenna impedance. The voltage standing wave ratio (VSWR) is within 2.0 from 1565 MHz to 1585 MHz, the r.f. bandwidth of the G.P.S. P signal, which indicates a good impedance match over the band of interest.

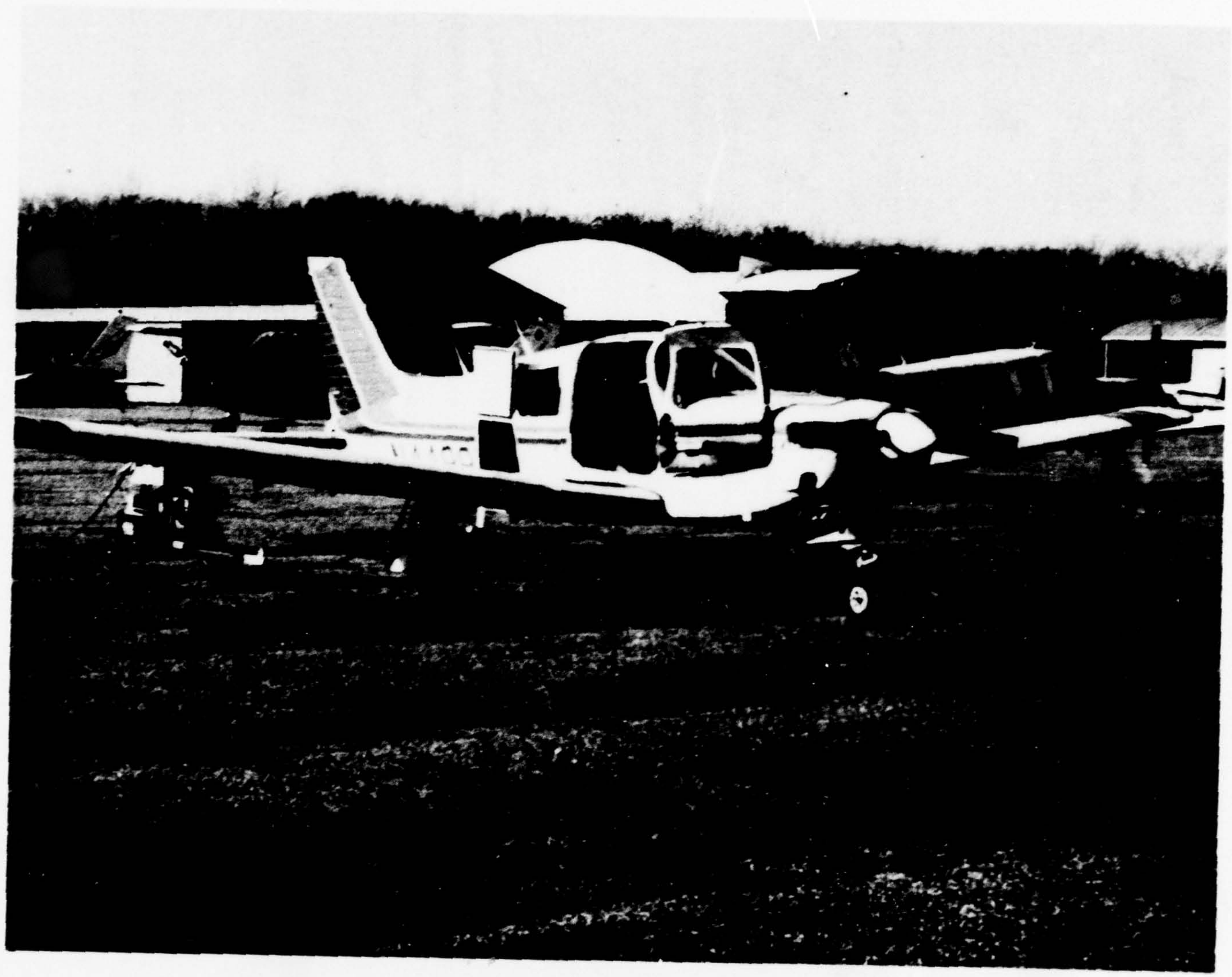

FIGURE 1. CHEROKEE ARROW III WITH R.F.I. MEASUREMENT SYSTEM

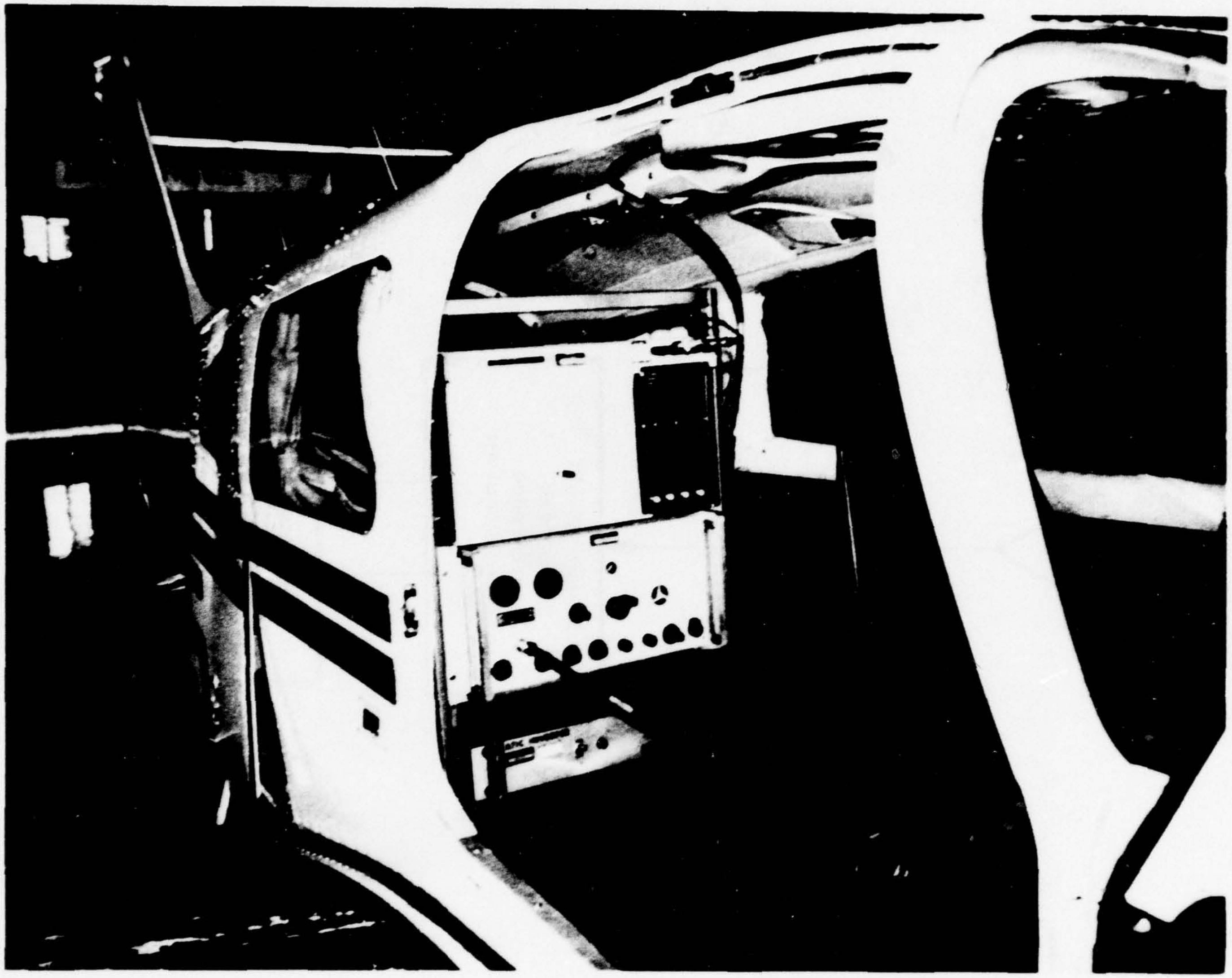

FIGURE 2. R.F.I. MEASUREMENT SYSTEM

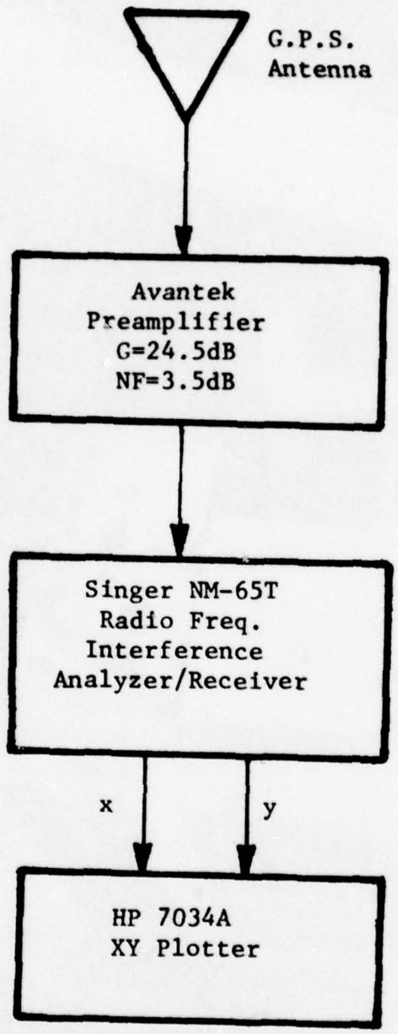

FIGURE 3. R.F.I. MEASUREMENT SYSTEM BLOCK DIAGRAM

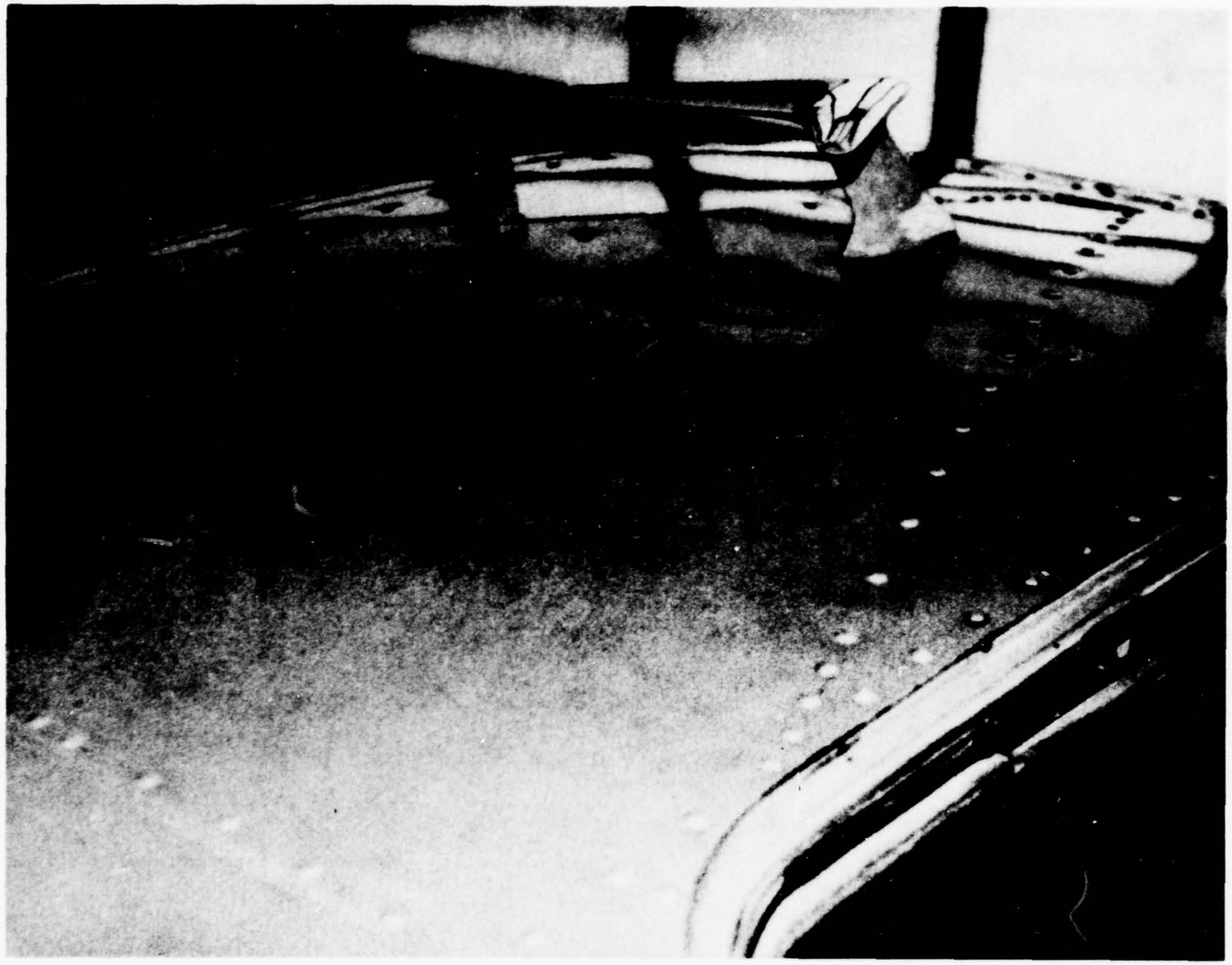

FIGURE 4. MICROSTRIP CROSSED SLOT ANTENNA

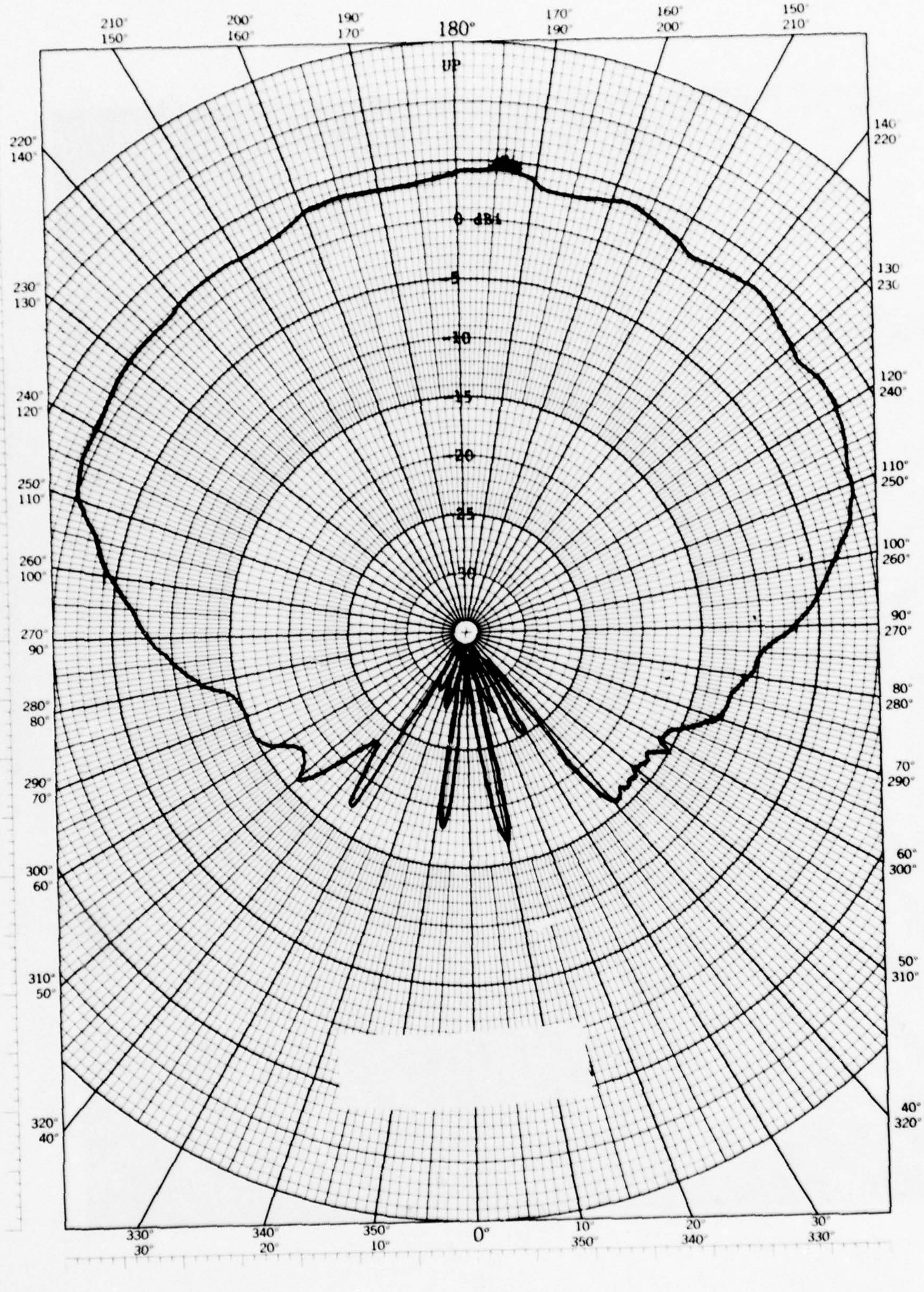

FIGURE 5. ANTENNA PATTERN

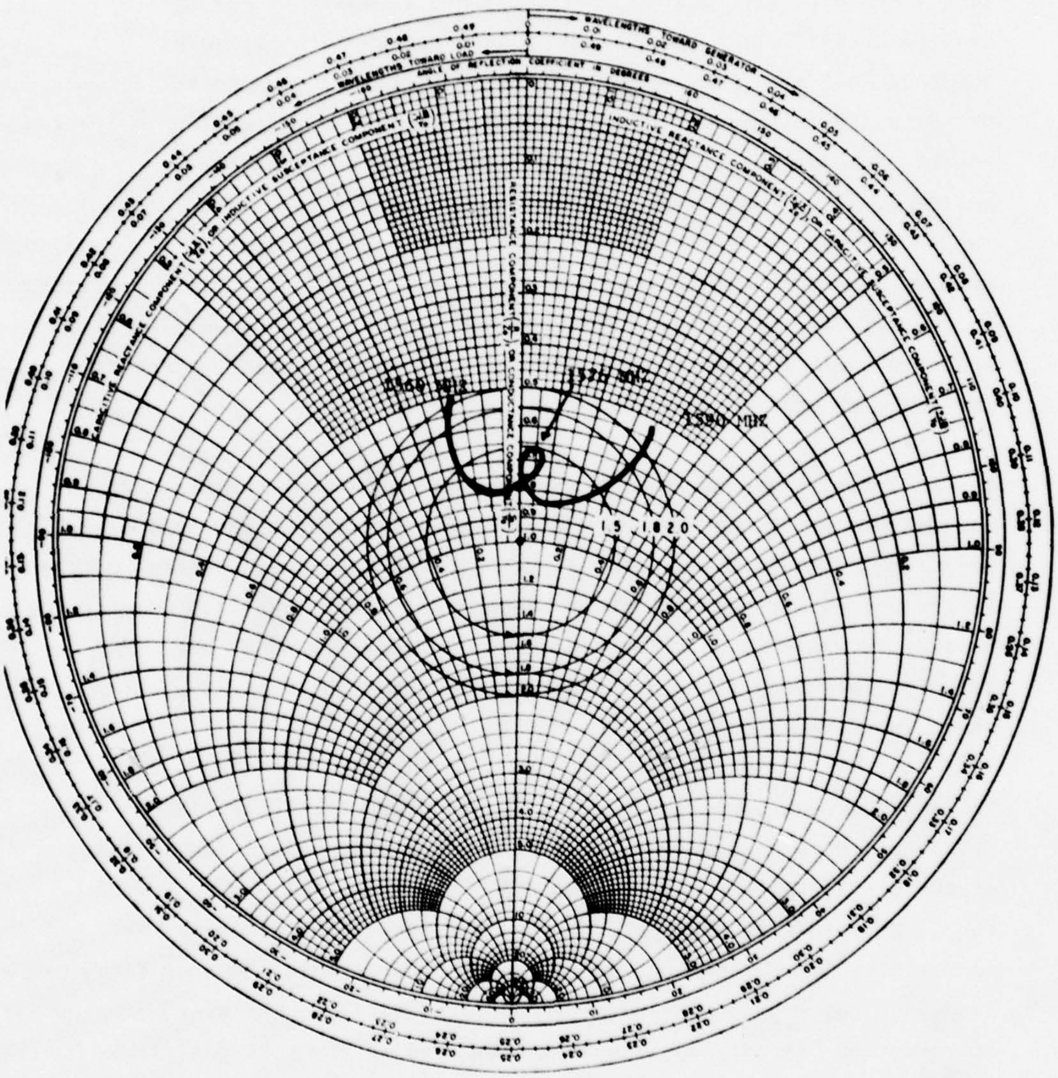

FIGURE 6. SMITH CHART RESPONSE OF ANTENNA

The output of the antenna was connected to the preamplifier via RG-214 cable. See Figure 7. This cable has a silvered copper conductor with silvered copper shielding braid and has an attenuation of .1dB/foot at 1575 MHz. See Ref. 1,6. The cable was three feet long, thus providing a loss of .3dB. The preamplifier was an Avantek AS-61T, which has 24.5dB of gain and a noise figure of 3.5dB at 1575 MHz. The output of the preamplifier goes to the Singer NM-65T Radio Interference Analyzer/Receiver (hereafter called analyzer); RG-214 cable was also used between the preamplifier and the analyzer. The X and Y outputs from the analyzer were used to drive the H.P. 7034A XY plotter. See Figure 8. The Y output is proportional to the detected power level and the X output is proportional to the selected frequency. Thus when the analyzer is tuned over the selected band, a graph of detected power versus frequency is recorded. The analyzer will be discussed next in detail.

The analyzer, a Singer NM-65T, was designed to detect the presence and measure the level and frequency characteristics of the received signal from 1.0 GHz to 10.0 GHz. See Figure 9. The frequency coverage of the instrument is divided into three bands; the first, 1.0 - 2.0 GHz, is the band of interest to us. The instrument is manually tuned over the selected frequency range and the results outputted to an XY plotter where they are recorded.

The analyzer can perform two types of measurements: Field intensity (F.I.) and Direct Peak (D.P.). Both of these can be made in any one of three selectable bandwidths (5 MHz, .5 MHz, and .1 MHz). Use of the .1 MHz bandwidth in the F.I. position yields the greatest CW sensitivity for the measurement of narrowband signals. Use of the 5 MHz bandwidth results in maximum broadband sensitivity. The average value of conducted or radiated signals is measured in the F.I. position. The peak value of conducted or radiated signals is measured in the D.P. position.

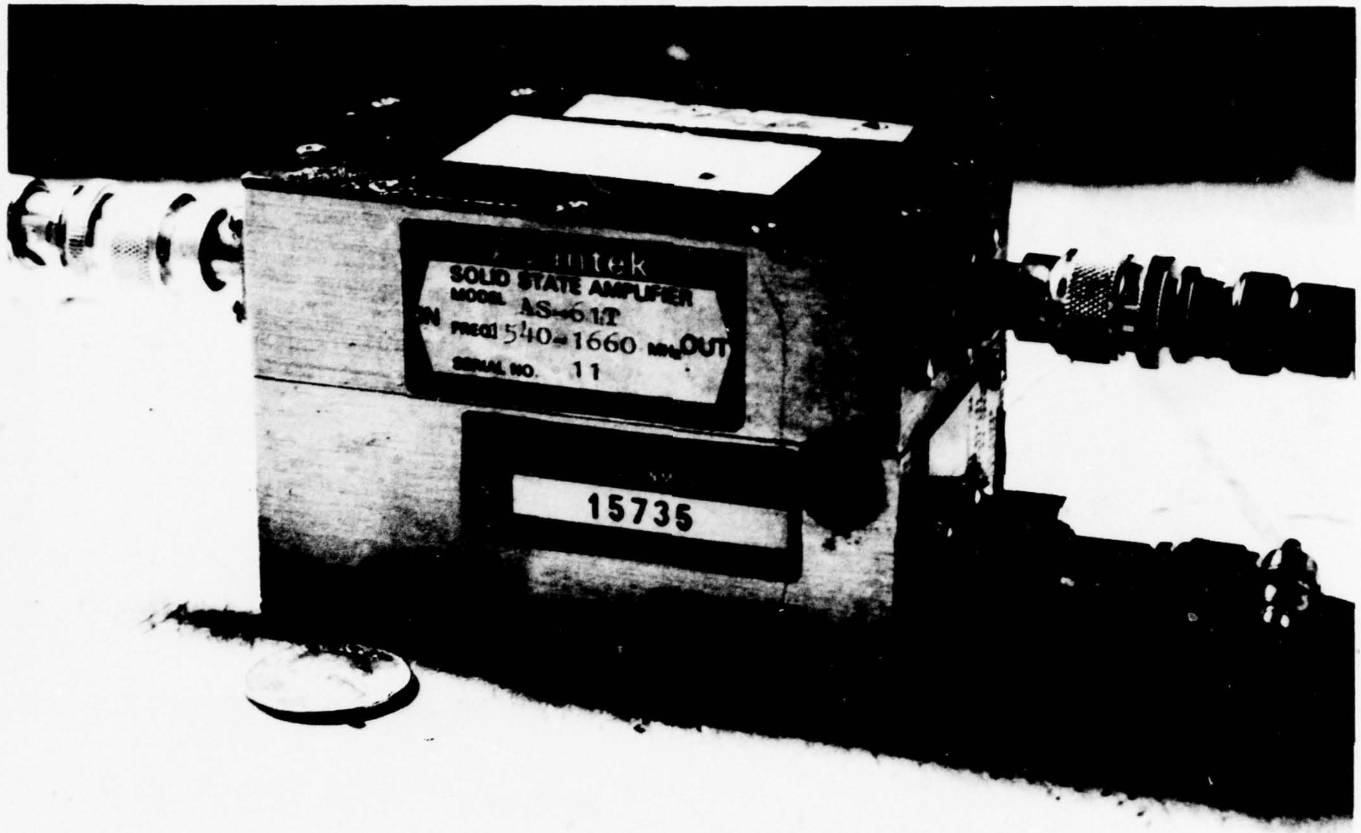

FIGURE 7. MEASUREMENT SYSTEM PREAMPLIFIER

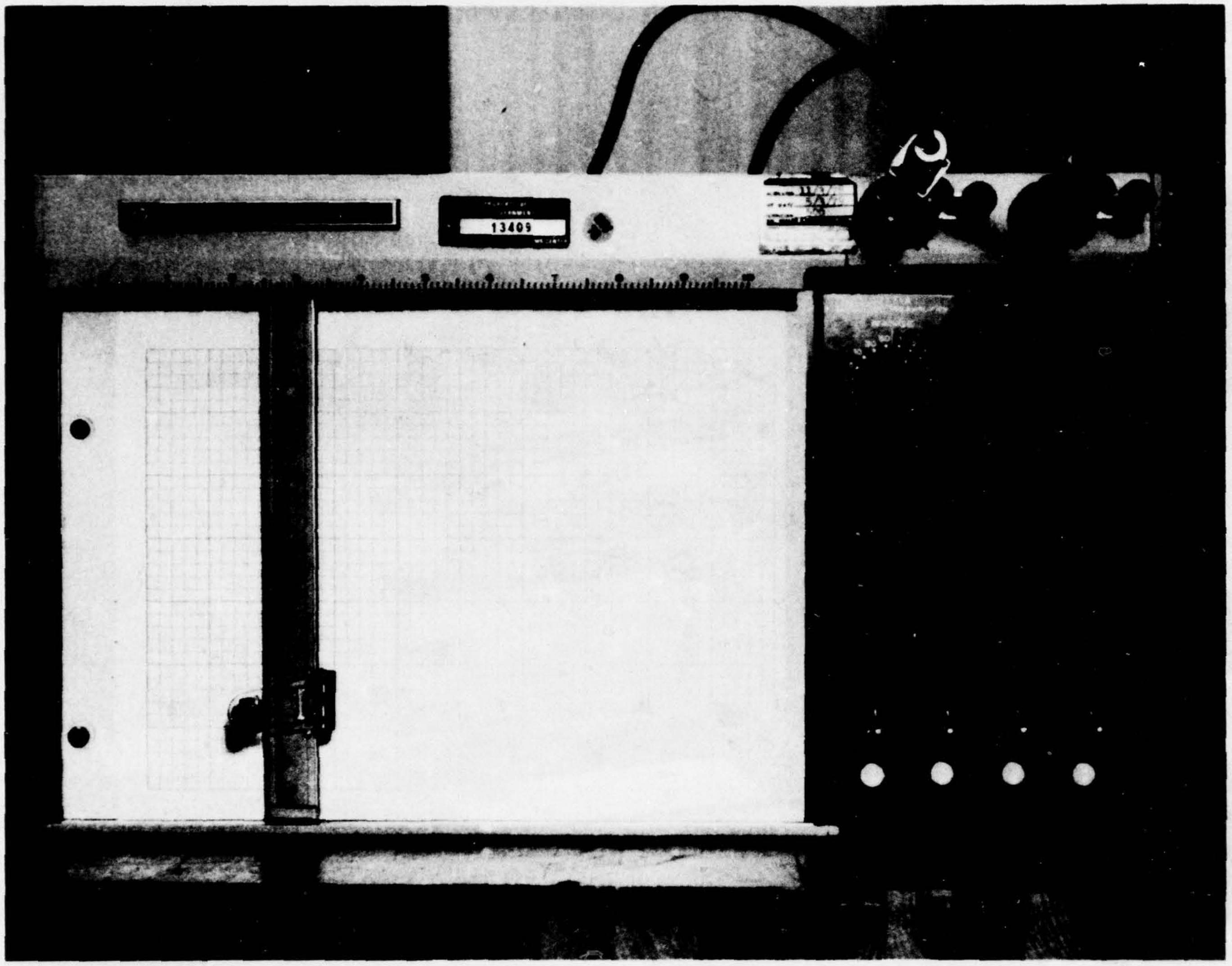

FIGURE 8. MEASUREMENT SYSTEM XY RECORDER

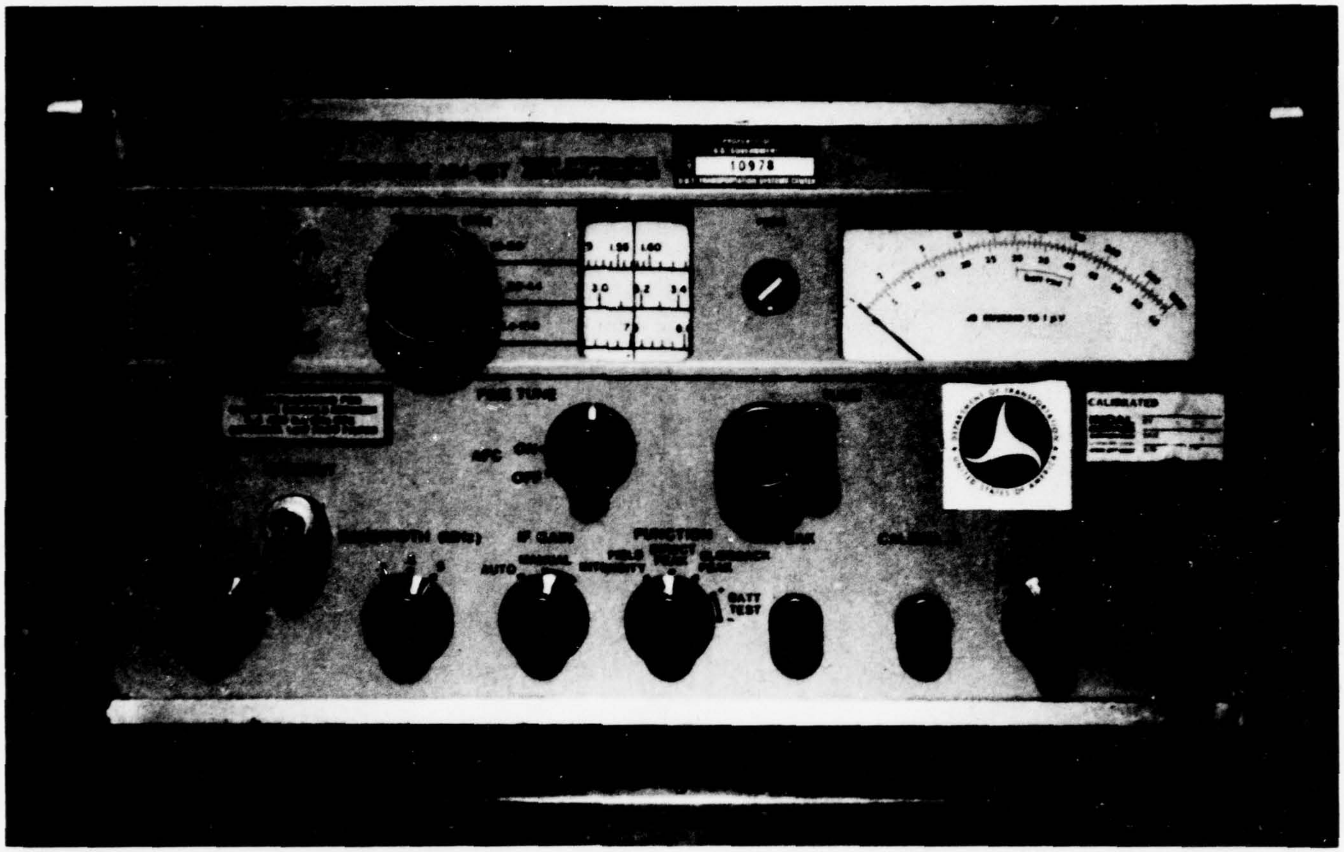

FIGURE 9. RADIO FREQUENCY INTERFERENCE ANALYZER/RECEIVER

The analyzer can be used to determine the level, characteristics and type of input by using a combination of tests. Narrowband discrete signals can be detected and measured by using the F.I. function. Starting at a wide bandwidth and decreasing it will insure maximum sensitivity. Use of the analyzer in the D.P. function will establish the peak levels. If changing the bandwidth from 5 MHz to .5 MHz results in no power level change, the input is narrowband. If the level drops 10 dB, the input is random noise; if there is less than a 10dB drop, the input is random but not white noise; if there is a 20dB drop, the noise is impulsive. Thus, the R.F.I. can be characterized by essentially six measurements, F.I. and D.P., in each of 3 different bandwidths.

The remaining piece of equipment used in the aircraft was the static inverter. It converted the aircraft power at 14 volts D.C. to 115 volts a.c., 60Hz, for the measurement electronics.

4.2 AIRCRAFT CALIBRATION SYSTEM

Prior to each flight, calibrations were performed to verify correct and accurate system performance. These calibrations established 1) that the total system including the antenna was tuned to receive electromagnetic energy in the band 1575.4 MHz ± 10 MHz and that the measurement system was detecting it and outputting it correctly and 2) the reference power level and the scale of each graph in dB per division.

First, an HP 8614B tuned to 1575.4 MHz was used with an L-Band antenna to act as a source of radiation to excite the G.P.S. antenna. The output on the XY recorder was observed and verified as correct.

Next, the measurement system was dynamically calibrated before and after each flight. See Figure 10. The input to the preamplifier from the antenna was disconnected and the signal source with the attenuator

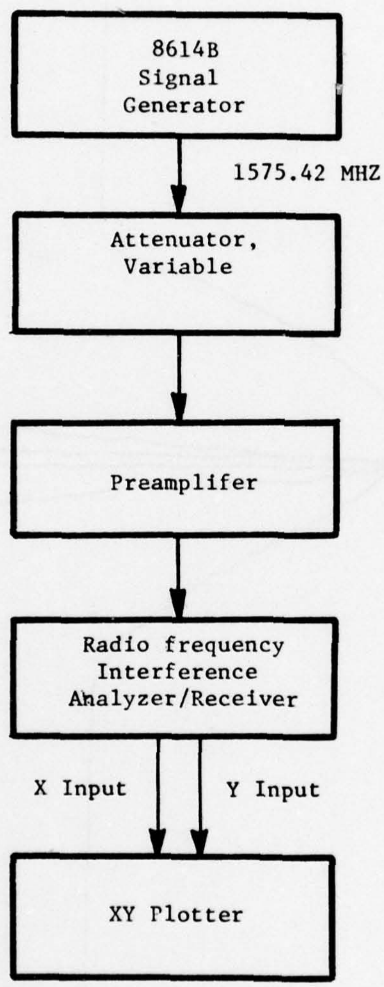

FIGURE 10. CALIBRATION SYSTEM BLOCK DIAGRAM

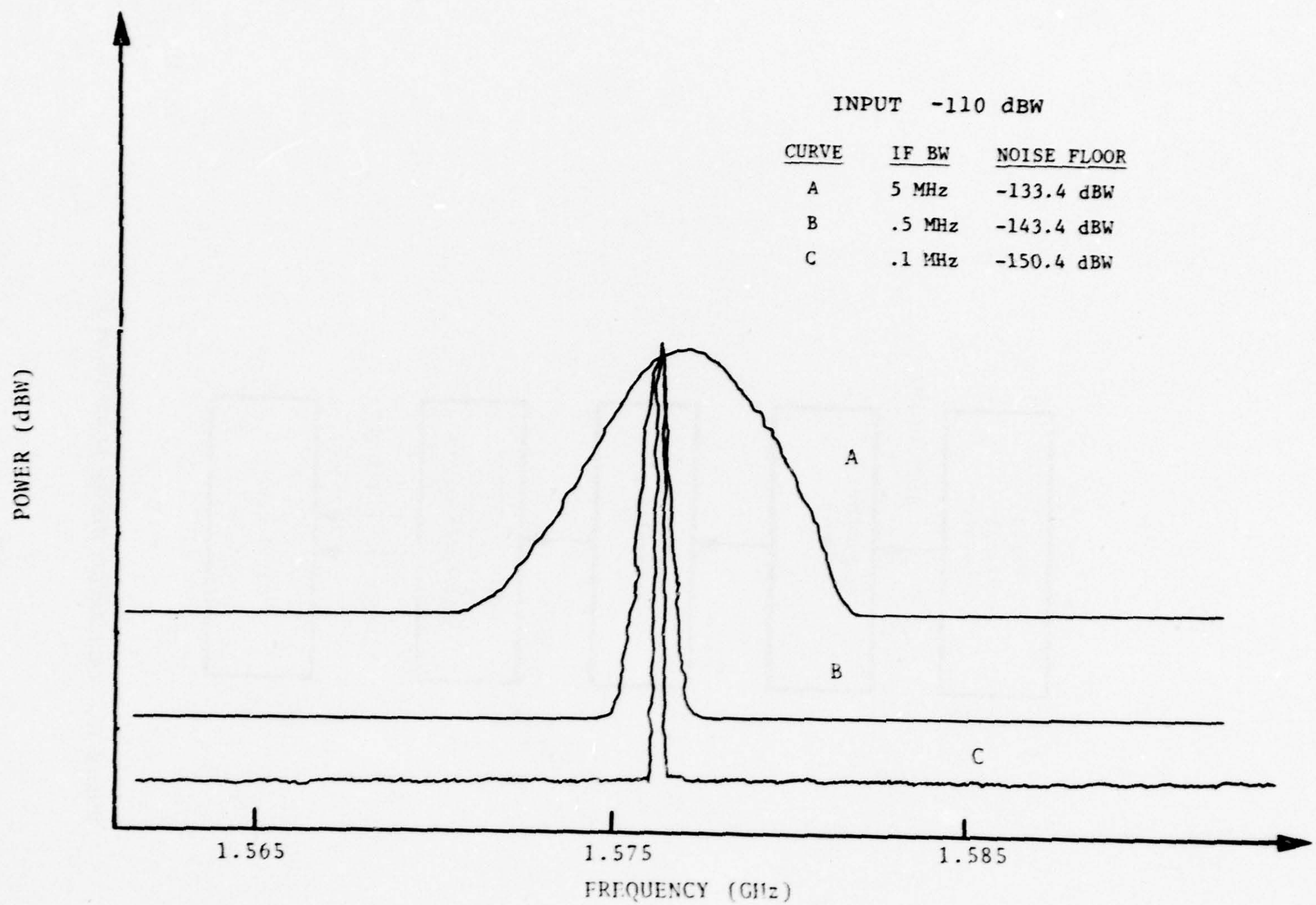

FIGURE 11. FIELD INTENSITY VS. FREQUENCY - INPUT -110 dBW

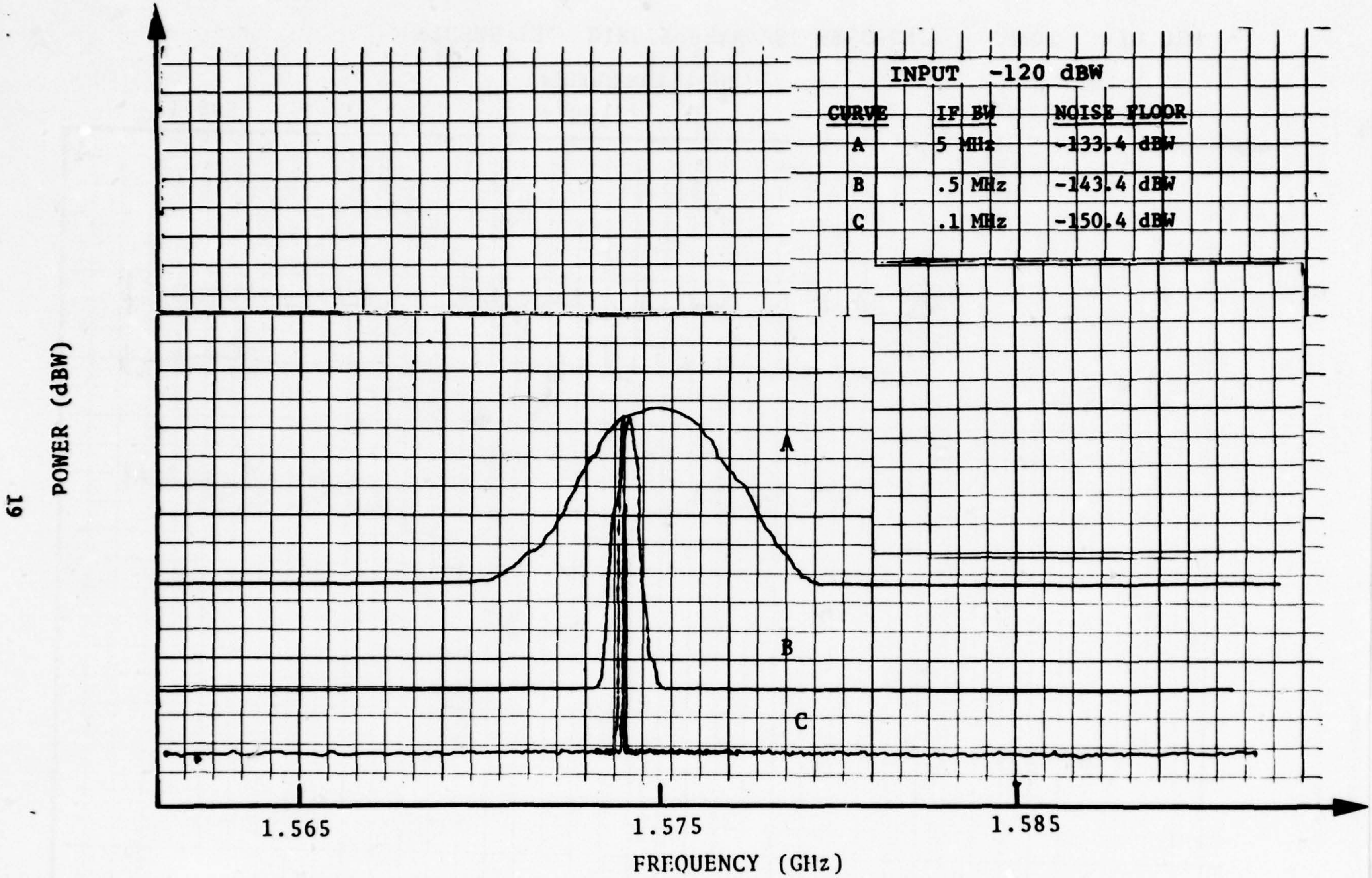

FIGURE 12. FIELD INTENSITY VS. FREQUENCY - INPUT -120 dBW

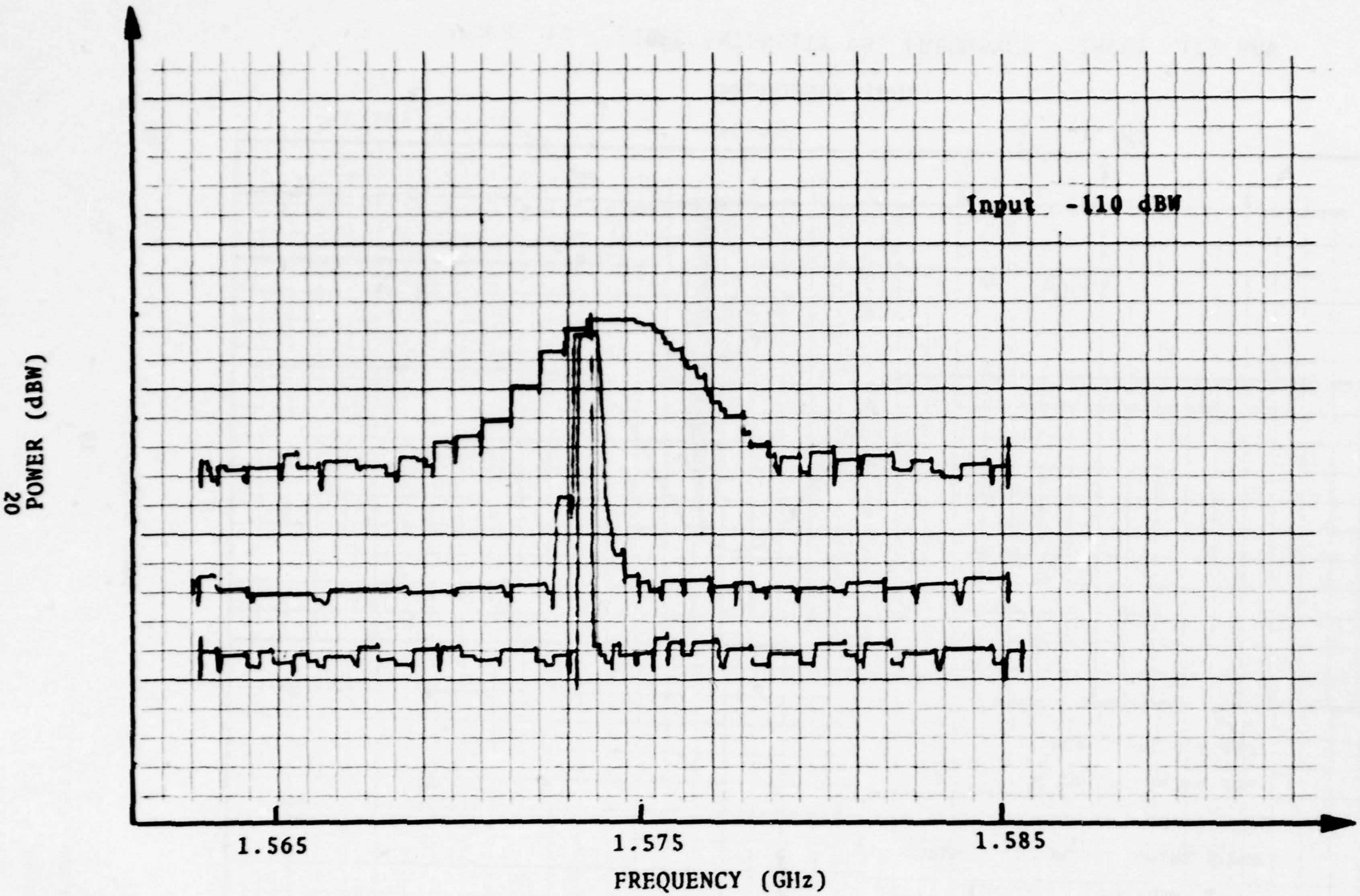

FIGURE 13. DIRECT PEAK VS. FREQUENCY - INPUT -110 DBW

connected as an input. All power measurements were made at the input to the preamplifier. Calibrations were carried out for both the field intensity and direct peak functions of the analyzer in all three bandwidths. See Figures 11, 12, and 13.

In Figures 11 and 12 typical calibration curves are shown of the measurement system when operated in the Field Intensity mode. Figure 13 is a calibration curve for the system operated in the direct peak mode. Each graph contains three curves, the result of tuning across the full 20 MHz G.P.S. band using each of the three different I.F. bandwidths. The input to the preamplifier in Figure 11 is -110dBW CW at 1575.4 MHz. Comparing curve A of Figure 11 with curve A of Figure 12 establishes that 10dB = 3.5 divisions.

The calibration system noise floor can be calculated as follows with reference to Figure 14.

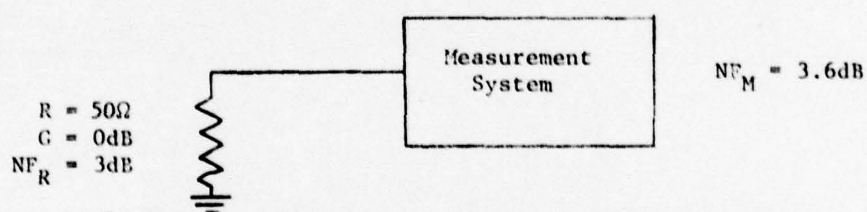

FIGURE 14. CALIBRATION SYSTEM NOISE FLOOR DETERMINATION BLOCK DIAGRAM

Note that the calibration system is the same as the measurement system except that the antenna has been replaced by the signal generator (Z_o = 50Ω). Thus the thermal noise floor is calculated:

$$N_o = KT_s$$

where $T_s = T_o \ (NF-1)$

and $NF = NF_R + \dfrac{NF_m - 1}{G_1}$

thus: $N_o = -200.4$ dBW/Hz

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The noise floor measured with the antenna connected as the input differs from the thermal noise reference and is calculated from eq. 2, 3, and 4 with T_s = 100°K, L =.3dB, T_o = 290°K and NF = 3.6dB. The result is: N_o = -201.7dBW/Hz, which is 1.3dB lower than the calibration system noise floor reflecting the lower value of sky noise as seen by the antenna as compared with the thermal noise of the resistor. Thus, knowing the calibration system noise floor level, and knowing that the measurement system noise floor is 1.3dB lower, the results of flight measurements can be quantified.

For measurements made using the 100KHz bandwidth the noise floor power reference level is -201.7dB/Hz + 50dB/Hz= -151.7dBW. Accordingly the power reference level of measurements made using the 500 KHz bandwidth is -144.7dBW, and for the 50dBHz bandwidth, -134.7dBW.

5. TEST PROCEDURE

Two hours before each flight the measurement system was powered to allow adequate warm-up time and to permit time for calibrations. Calibrations were performed as explained in the section on aircraft calibration system. As soon as the calibrations were completed, the aircraft flew the patterns designated for that day.

Each R.F.I. measurement consisted of a series of 6 individual measurements and resulted in 6 separate graphs of received "signal" power versus frequency. Three were recorded using the field intensity mode of the analyzer, one in each of the three selectable I.F. bandwidths, and three in the direct peak mode, also using each of the three different I.F. bandwidths. Thus, one series of six measurements were taken to characterize the RFI at a given point in a flight.

The data was recorded on paper charts in real time. There was no need for computer processing and no on-board computer system was required.

6. RESULTS

The data was collected during five flights, each flight lasting approximately four hours. Each flight consisted of nine to sixteen series of tests. Each series consisted of six measurements; field intensity measurement made in 3 different I.F. bandwidths and direct peak measurement made in 3 different bandwidths. The data collected is summarized in Table 1. This table lists the data by date and the conditions under which it was collected. R.F.I. measurements were performed during the day and night, at three airports, two municipal and one major commercial U.S. airport. Flights were at various altitudes from 2000 to 12,000 feet. in rural and urban areas, in holding patterns at the airports while climbing and descending, and while on the ground. Presentation of all the data would be excessive since each day produced 60 to 70 graphs plus calibrations: Over 400 graphs were obtained. In many cases, the result of one series of measurements is the same as another and no different information is revealed. Thus, representative data will be presented which characterizes each general situation.

The results of the measurements made using the field intensity mode of the system in each of the three different I.F. bandwidths are presented on the same graph. The thermal noise floor indicated is for the I.F. bandwidth of 100KHz. The thermal noise floor for the measurement using one of the other two available I.F. bandwidths is proportionally higher by the ratio of the bandwidths, but the measurement using the 100KHz bandwidth is the most significant since it provides the greatest system sensitivity.

For direct peak measurements each graph presents the results recorded for the I.F. bandwidth stated. Measurements made using the 5 MHz and .5 MHz bandwidths are the most significant since the noise is wideband. Thus, for direct peak measurements, results are presented for these two bandwidths only. The thermal noise floor indicated is that calculated for the I.F. bandwidth selected and is the average value of the received power. For thermal noise, peak values are generally 8-12 dB above the average value.

TABLE 1. SUMMARY OF DATA COLLECTION

Date - 12/6/78 DAY 1

TIME - 1:00 PM - 4:00 PM

WEATHER - Clear, 40 - 50° F

Series	Area	Alt (ft)	Pattern
1	Norwood Airport	800	Square around airport
2	Norwood Airport	800	Holding pattern (near TV towers)
3	Norwood Airport	1500	Holding pattern (quiet area)
4	Rural	1500-8000	Climbing (500ft/min)
5	Rural	10,000	flat
6	Rural	8000	flat
7	Rural	6000	flat
8	Rural	4000	flat
9	Rural	2000	flat
10	Norwood	0	ground

TABLE 1 (continued)

Date - 12/7/78 DAY 2

TIME - 1:00 PM - 3:00 PM

WEATHER - Clear, high thin, 45°F

Series	Area	Alt (ft)	Pattern
1	Norwood Airport	1500	Square pattern around airport
2	Norwood Airport	1500	holding pattern (near TV towers)
3	Norwood Airport	1500	holding pattern (quiet area)
4	Rural	2000	flat
5	Rural	4000	flat
6	Rural	6000	flat
7	Rural	8000	flat
8	Rural	10,000	flat
9	Rural	12,000	flat
10	Rural		descending (800ft/min)

TABLE 1 (Continued)

Date - 12/11/78 DAY 3

TIME - 7:30 PM - 11:00 PM

WEATHER - Clear, 20°F

Series	Area	Alt (ft)	Pattern
1	Norwood Airport	1500	Square pattern around airport
2	Logan Airport	1500	holding pattern, south of Boston
3	Logan Airport	2000	holding pattern, north of Boston
4	Boston	2000	flat
5	Boston	5000	Descending (500ft/min)
6	Logan Airport	0	On ground
7	Boston	3300	Climbing (500ft/min)
8	Boston	6000	flat
9	Boston	8000	flat
10	Boston	10,000	flat
12	Boston	4000	flat
13	Norwood Airport	0	ground

TABLE 1 (Continued)

Date - 12/12/78 DAY 4

TIME - 12:00 - 4:00 PM

WEATHER - cloudy, 35°F

Series	Area	Alt (ft)	Pattern
1	Boston	1500	holding pattern, south Boston
2	Boston	2000	flat
2a	Boston	2000	flat
3	Boston	1500	holding pattern, north of Boston
4	Boston	4000	Descending (700 ft/min)
5	Logan Airport	0	Ground
6	Boston	0-1500	Climbing (500ft/min)
7	Boston	4000	flat
7a	Boston	4000	flat
8	Boston	6000	flat
8a	Boston	6000	flat
9	Boston	8000	flat
9a	Boston	8000	flat
10	Boston	10,000	flat
10a	Boston	10,000	flat
11	Boston	12,000	flat
11a	Boston	12,000	flat

TABLE 1 (Continued)

Date - 12/13/78 DAY 5

TIME - 1:00 - 4:00 PM

WEATHER - Partly cloudy, 40°F

Series	Area	Alt (ft)	Pattern
1	Norwood Airport	1500	holding pattern (near TV towers)
2	Norwood Airport	1500	holding pattern (quiet area)
3	Norwood to Hanscom Field Airport	1500-0	Descending (500ft/min)
5	Hanscom Field Airport	0-2000	Climbing (500ft/min)
6	Boston	2,000	flat
7	Over Ocean	3,000	flat
8	Boston	4,000	flat
9	Boston	6,000	flat
10	Boston	8,000	flat
11	Boston	10,000	flat
12	Boston	10,000	flat
13	Boston	4,000	flat
14	Boston	2,500	flat

Thus, only the noise peaks above the thermal peaks are due to R.F.I.

The results of the R.F.I. measurement program are shown in Figures 15-40. The results chosen for inclusion represent a sample of the aggregate and in fact have been selected to represent a cross section of all the results. Table 2 lists the included data and the conditions under which it was obtained.

Examination of the results obtained which represent the average value of the R.F.I., recorded in the field intensity mode, shows no narrowband discrete high power signals appearing in the band. This implies that the r.m.s. value of the R.F.I. was small enough in comparison with the r.m.s. thermal noise floor that the latter was the predominant noise source.

Examination of all data obtained using the direct peak mode of the system yields information about the peak values of the noise. The peak values in the lower half of the band, 1565 MHz to 1575 MHz, were higher than in the upper half of the band, 1575 MHz to 1585 MHz. The peak values in the lower half tended to be 15-20 dB above thermal while in the upper half they were 5-15 dB above thermal. In all cases, there were occasional noise bursts which resulted in peaks twenty to thirty dB above the noise floor. However, since the field intensity measurement never showed any measureable r.m.s. value above thermal it is concluded that the r.m.s. value of the energy content of this impulsive R.F.I. was below the r.m.s. noise floor. Even though the noise peaks were higher in the lower half of the band, again the same conclusions are reached, i.e. the r.m.s. energy content of the R.F.I. is below that of the r.m.s. thermal noise floor. Switching from a measurement bandwidth of 5 MHz to .5 MHz resulted in a 20 dB drop in the noise peak value, in most cases. The conclusion is that the R.F.I. is broadband impulsive noise with some random noise.

TABLE 2. SUMMARY OF DATA CONDITIONS

Figures	Measurement	Condition
15-17	low altitude	rural
18-20	high altitude	rural
21-23	low altitude	urban
24-26	high altitude	urban
27-29	holding pattern	Norwood Municipal Airport
30-32	holding pattern	Logan International Airport
33-35	climbing	urban
36-38	descending	urban
39-40	on ground	expanded frequency scale

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The reason for the higher values of noise peaks in the lower half of the band when compared with the upper half can be seen by referring to figures 39 and 40, direct peak measurements made over a wider frequency range, 200 MHz. It is clearly evident that there is a noise source centered near 1551 MHz about 20 MHz wide. The peaks are 20 dB above the thermal peaks at all times. Further examination showed the following : 1) this noise was present only when the aircraft engine was on and not present when the aircraft was on the ground powered by an external power cart, 2) the noise was coupled in through the antenna and not picked up by the measurement system power leads to the aircraft, 3) the noise was recorded during all flights, regardless of location, altitude, or time of day. The conclusion is that the noise is developed by the aircraft engine system and coupled in by the antenna. The average value is below that of the system noise but high enough to be peak detected. A typical GPS receiver might have a processing gain of 60 dB for C/A signal reception but the actual value would depend on the particular design implemented. Ref. 4. This means that any narrowband signal is reduced by 60 dB and spread over the C/A signal bandwidth, 2 MHz, which then contributes to the thermal noise floor. The power content of the random interference measured here is so low that the effect on the overall system operation is negligible.

In order to eliminate the possibility of antenna malfunction as a source of this observed noise, two different antennas (samples of the same design) were tried. However, the results obtained were identical.

It should be emphasized that these results are valid for the antenna used on a Cherokee Arrow III flying in the Boston, Mass. area in a winter environment. Although the results can be considered typical for this type of system in a statistical sense, the R.F.I. may vary from one geographical area to another and perhaps from one season to another. It should also be expected that the interaction between the antenna and a different aircraft might result in a different response than that seen here.

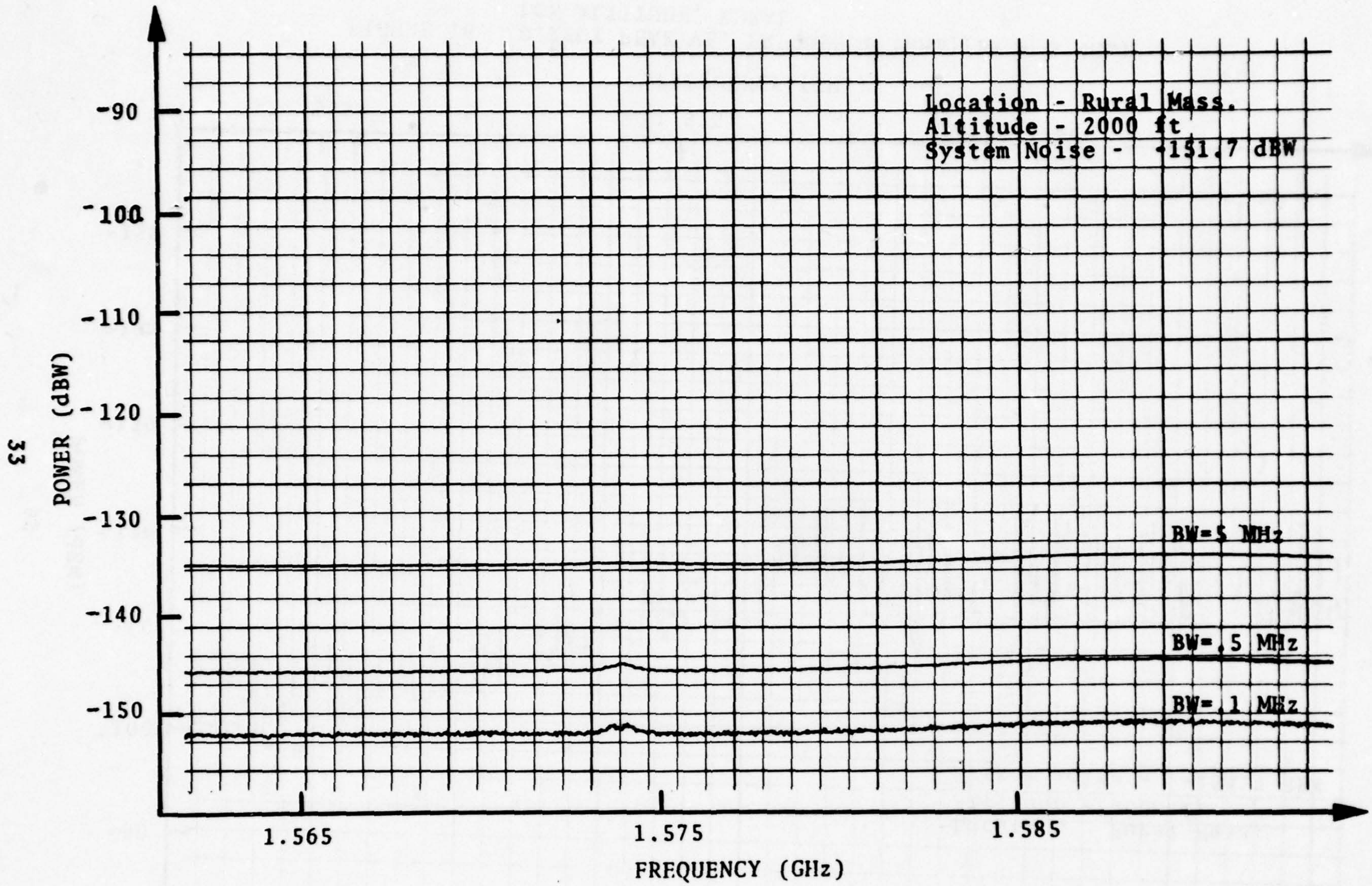

FIGURE 15. FIELD INTENSITY VS. FREQUENCY (GHz)
LOW ALTITUDE, RURAL

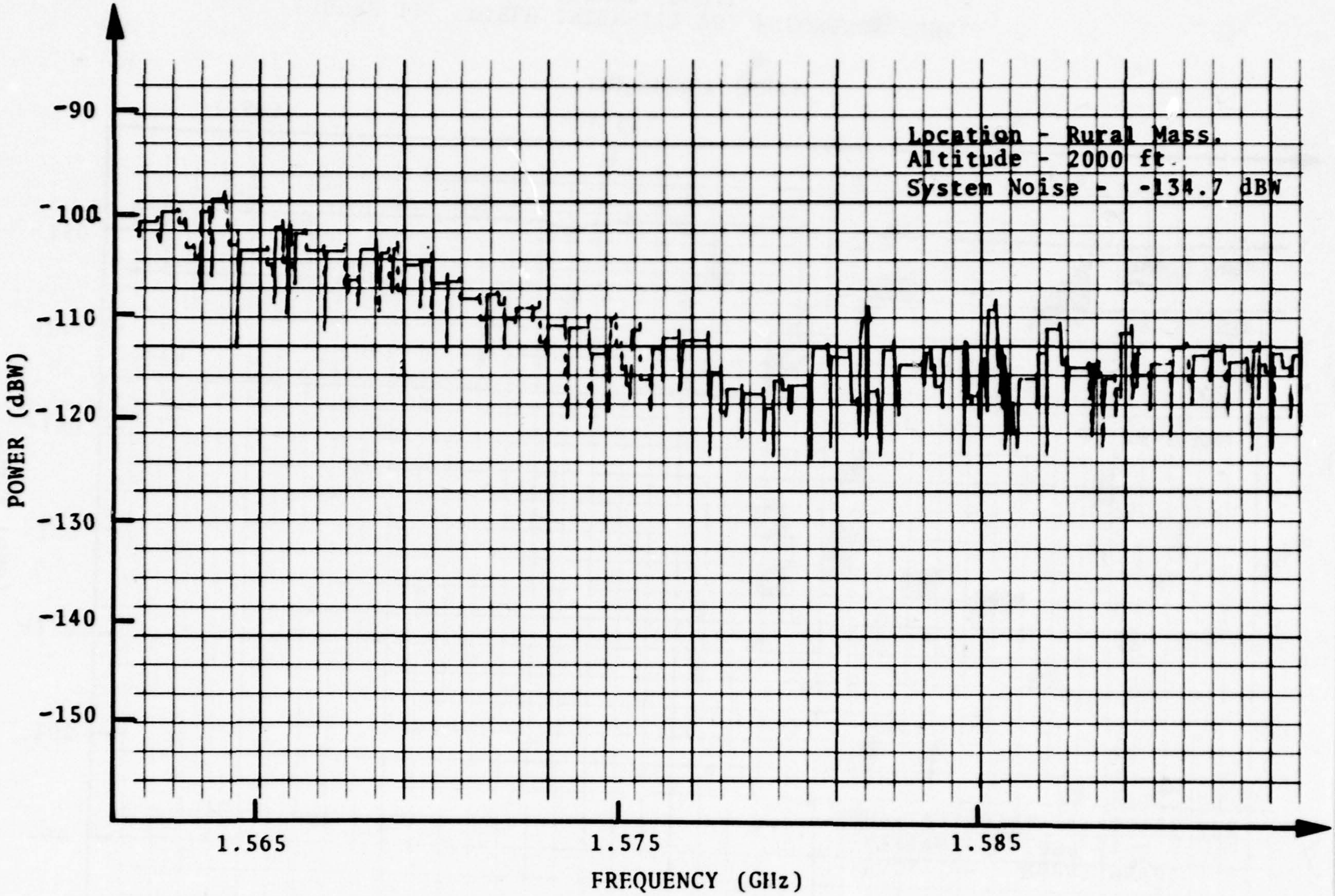

FIGURE 16. DIRECT PEAK VS. FREQUENCY (GHz)(BW = 5 MHz)
LOW ALTITUDE, RURAL

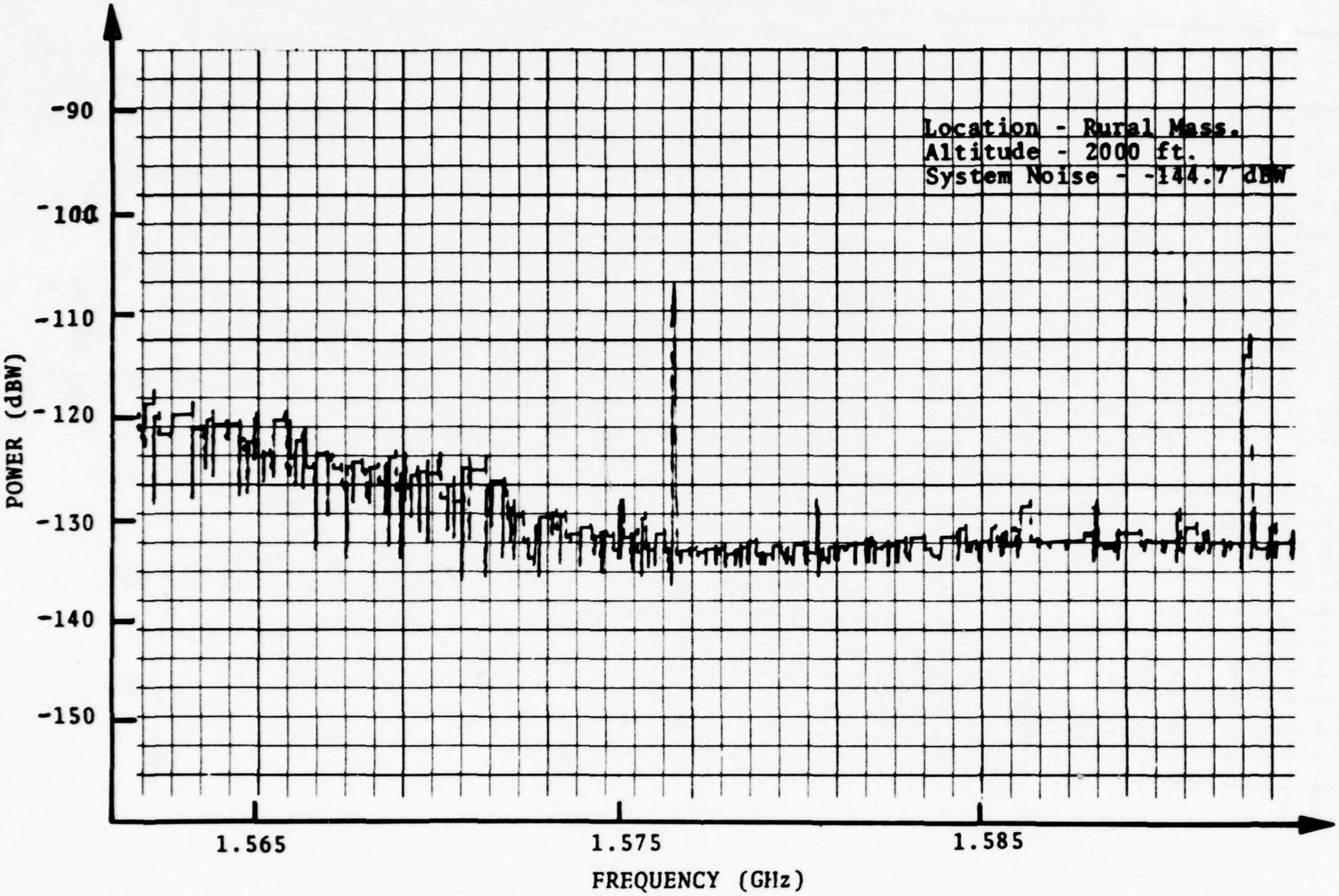

FIGURE 17. DIRECT PEAK VS. FREQUENCY (GHz)(BW = .5 MHz) LOW ALTITUDE, RURAL

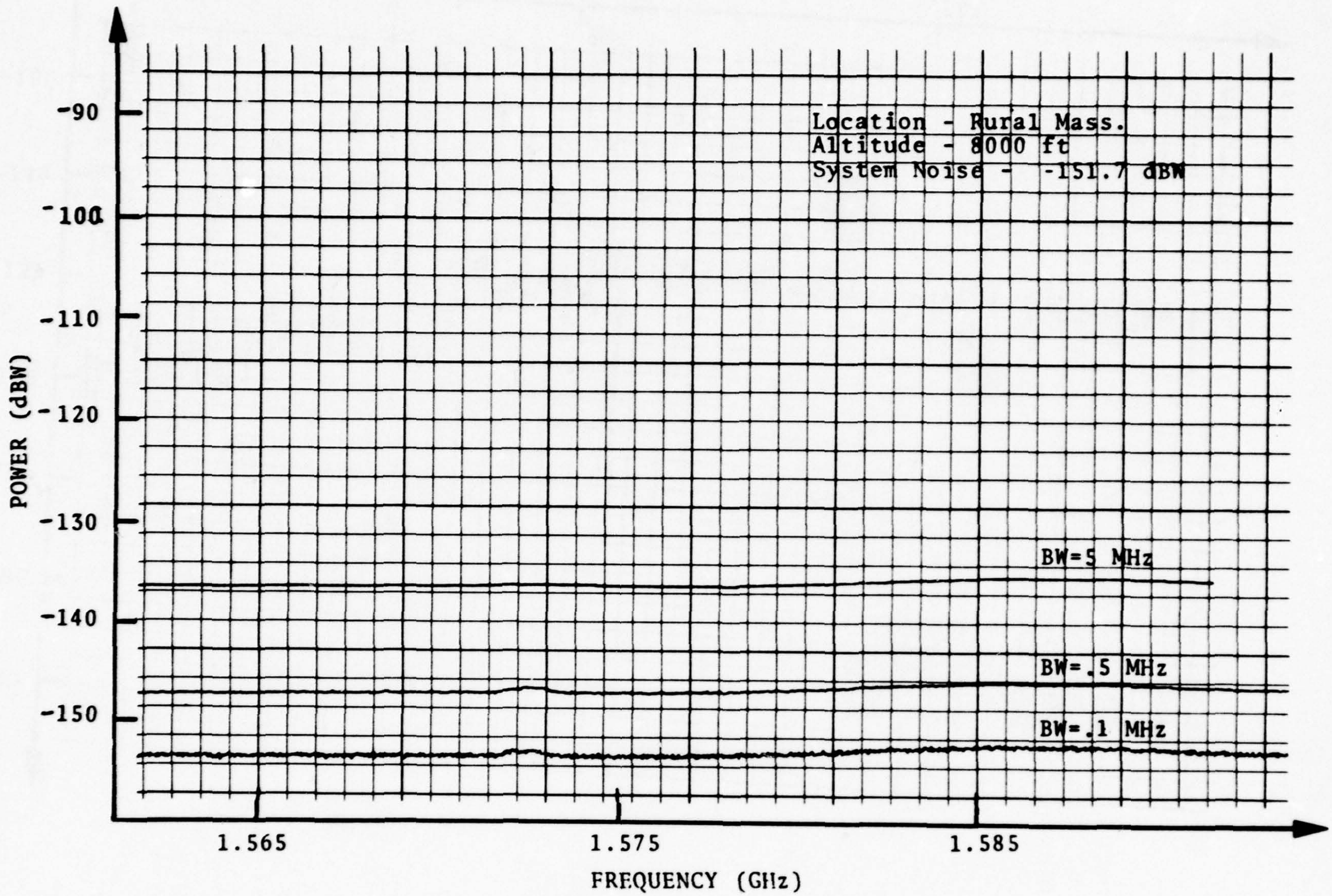

FIGURE 18. FIELD INTENSITY VS. FREQUENCY (GHz)
HIGH ALTITUDE, RURAL

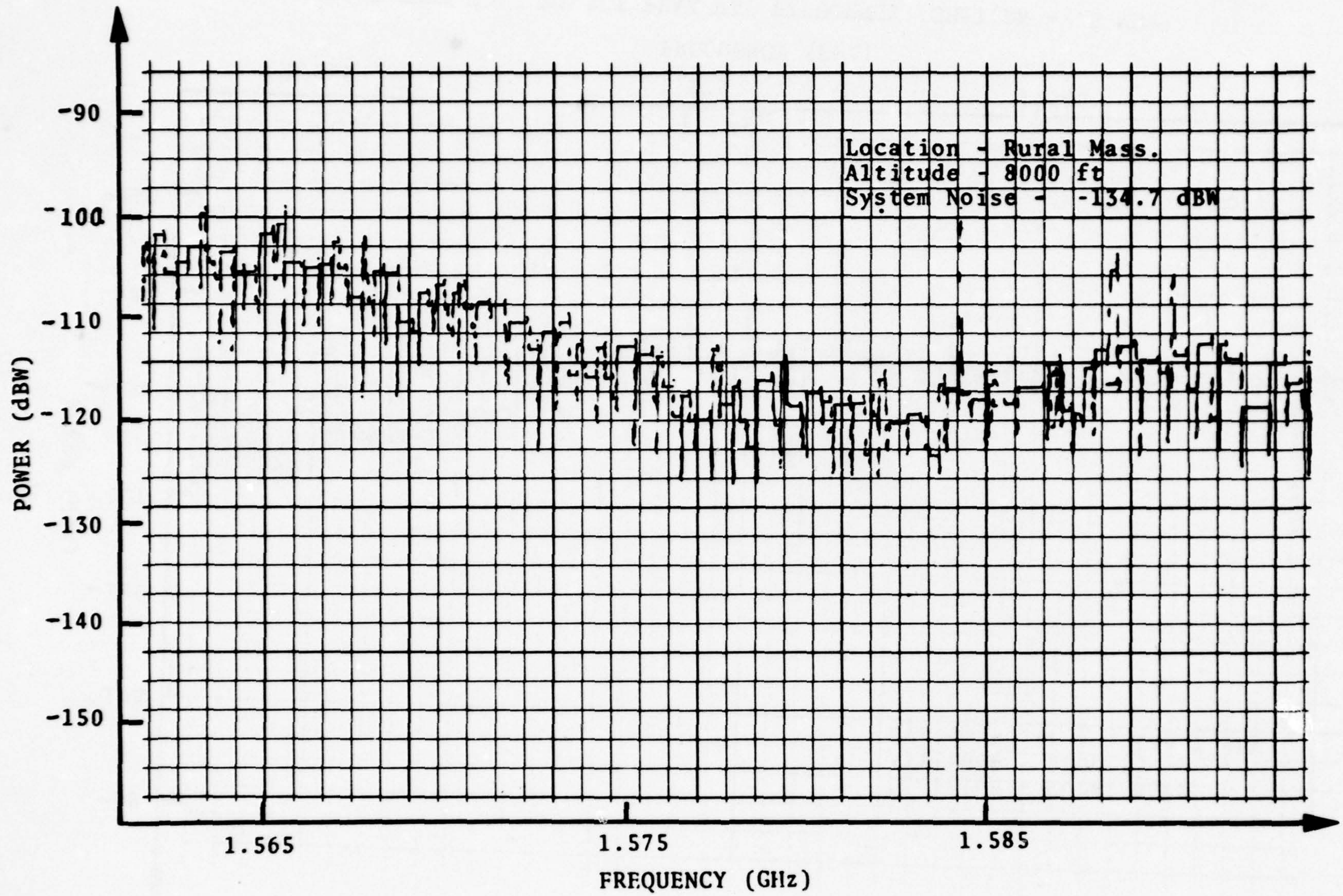

FIGURE 19. DIRECT PEAK VS. FREQUENCY (GHz)(BW = 5 MHz)
HIGH ALTITUDE, RURAL

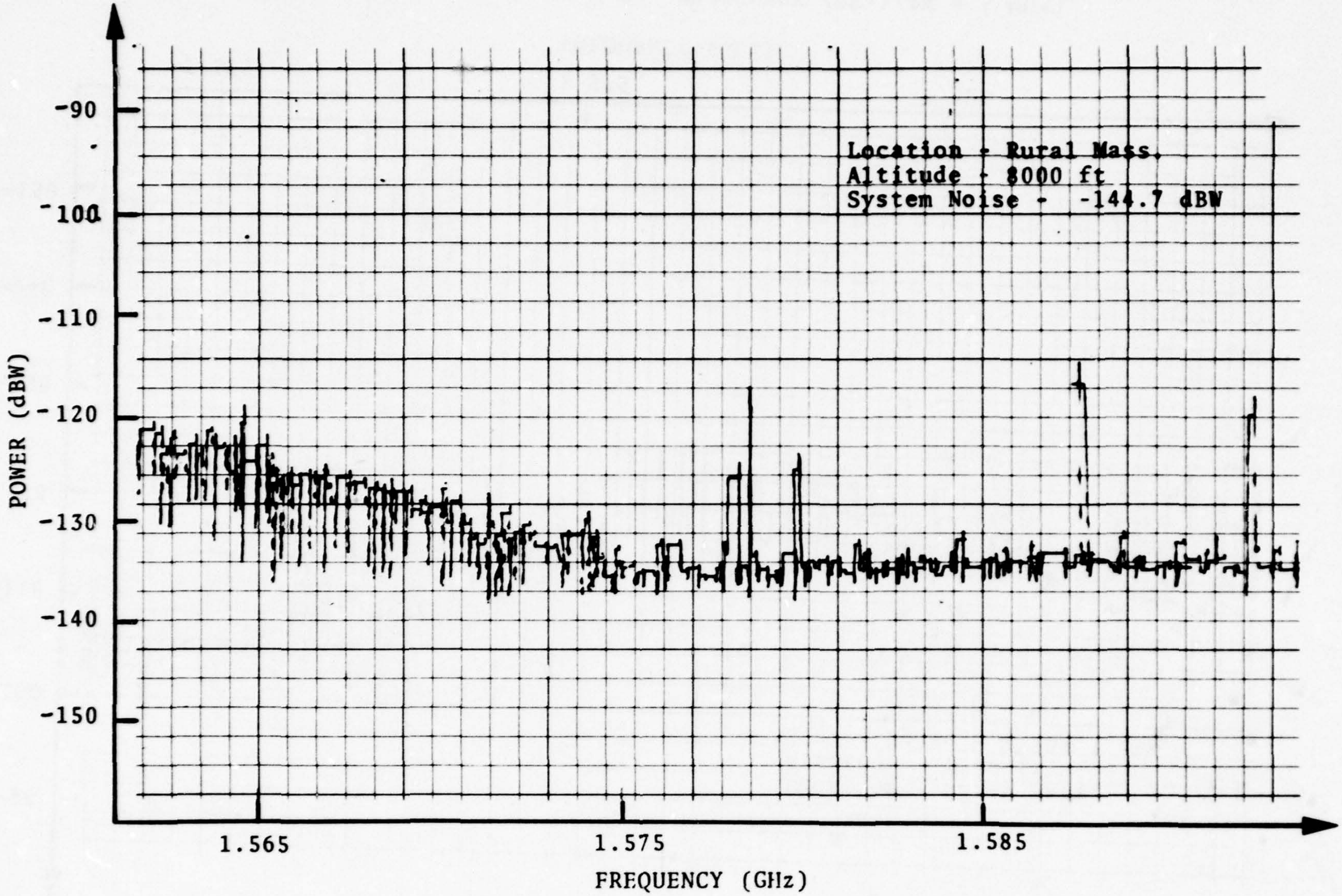

FIGURE 20. DIRECT PEAK VS. FREQUENCY (GHz) (BW = .5 MHz)
HIGH ALTITUDE, RURAL

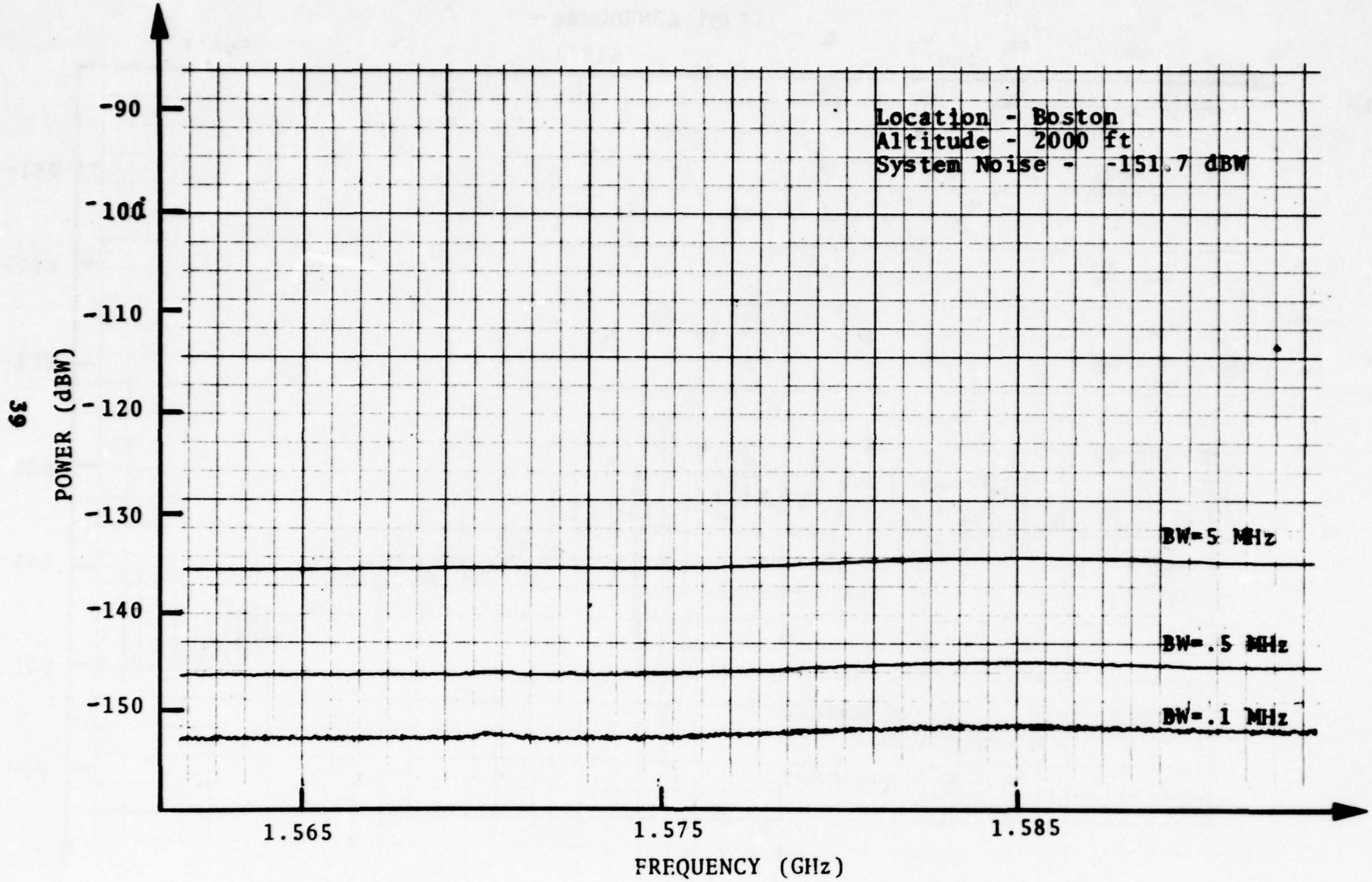

FIGURE 21. FIELD INTENSITY VS. FREQUENCY (GHz) (BW = .5 MHz)
LOW ALTITUDE, URBAN

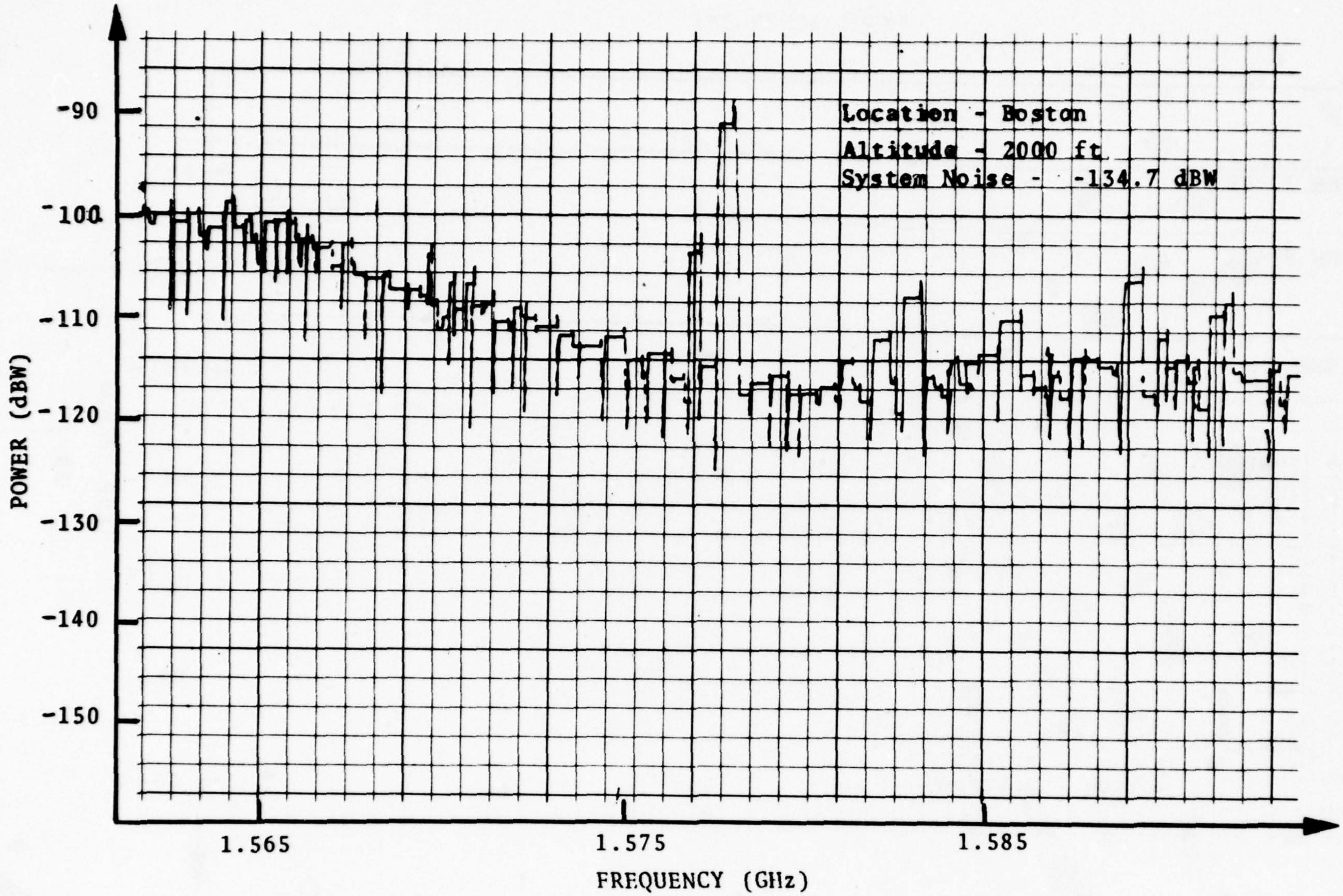

FIGURE 22. DIRECT PEAK VS. FREQUENCY (GHz)(BW = 5 MHz)
LOW ALTITUDE, URBAN

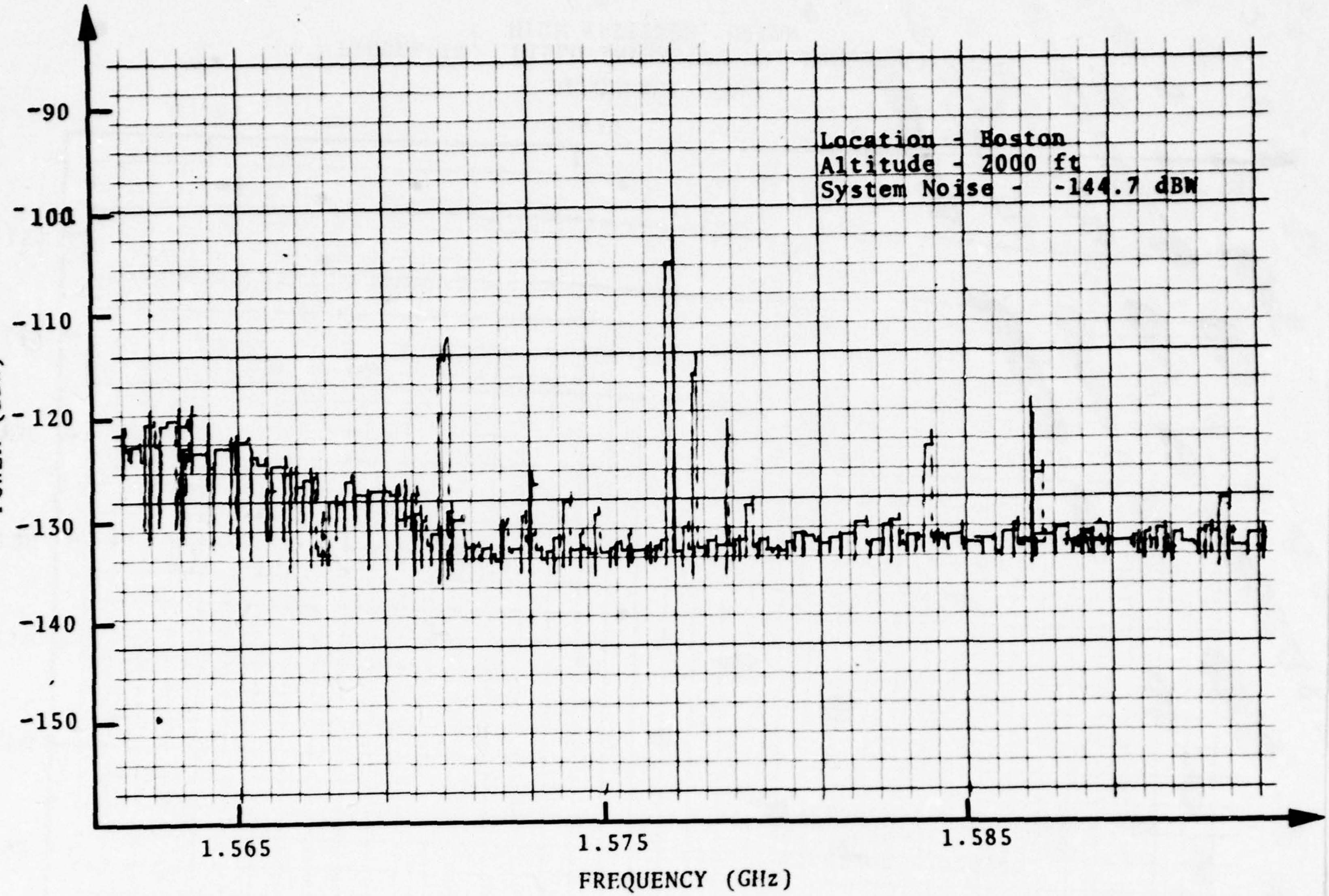

FIGURE 23. DIRECT PEAK VS. FREQUENCY (GHz)(BW = .5 MHz)
LOW ALTITUDE, URBAN

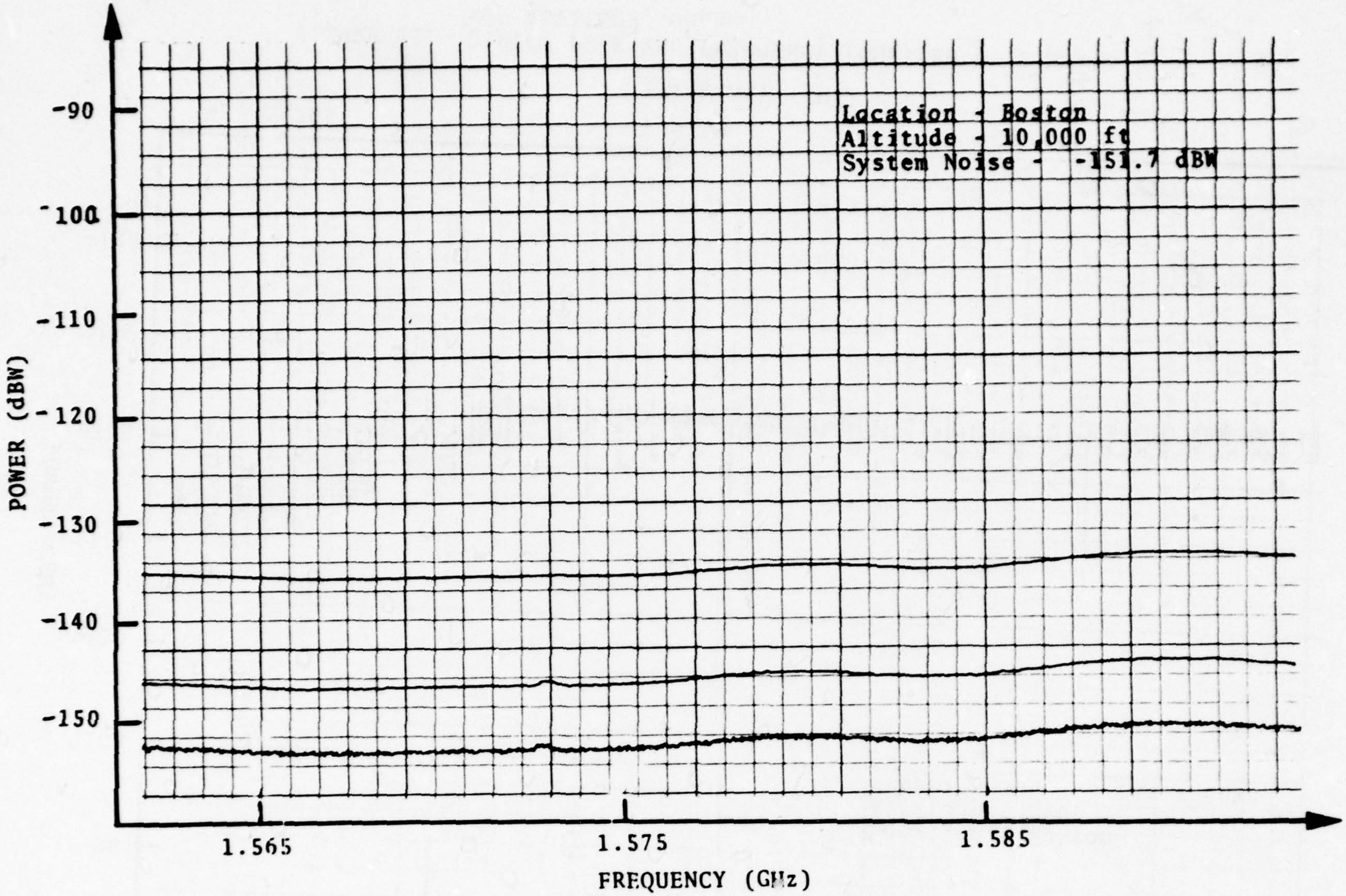

FIGURE 24. FIELD INTENSITY VS. FREQUENCY (GHz)
HIGH ALTITUDE, URBAN

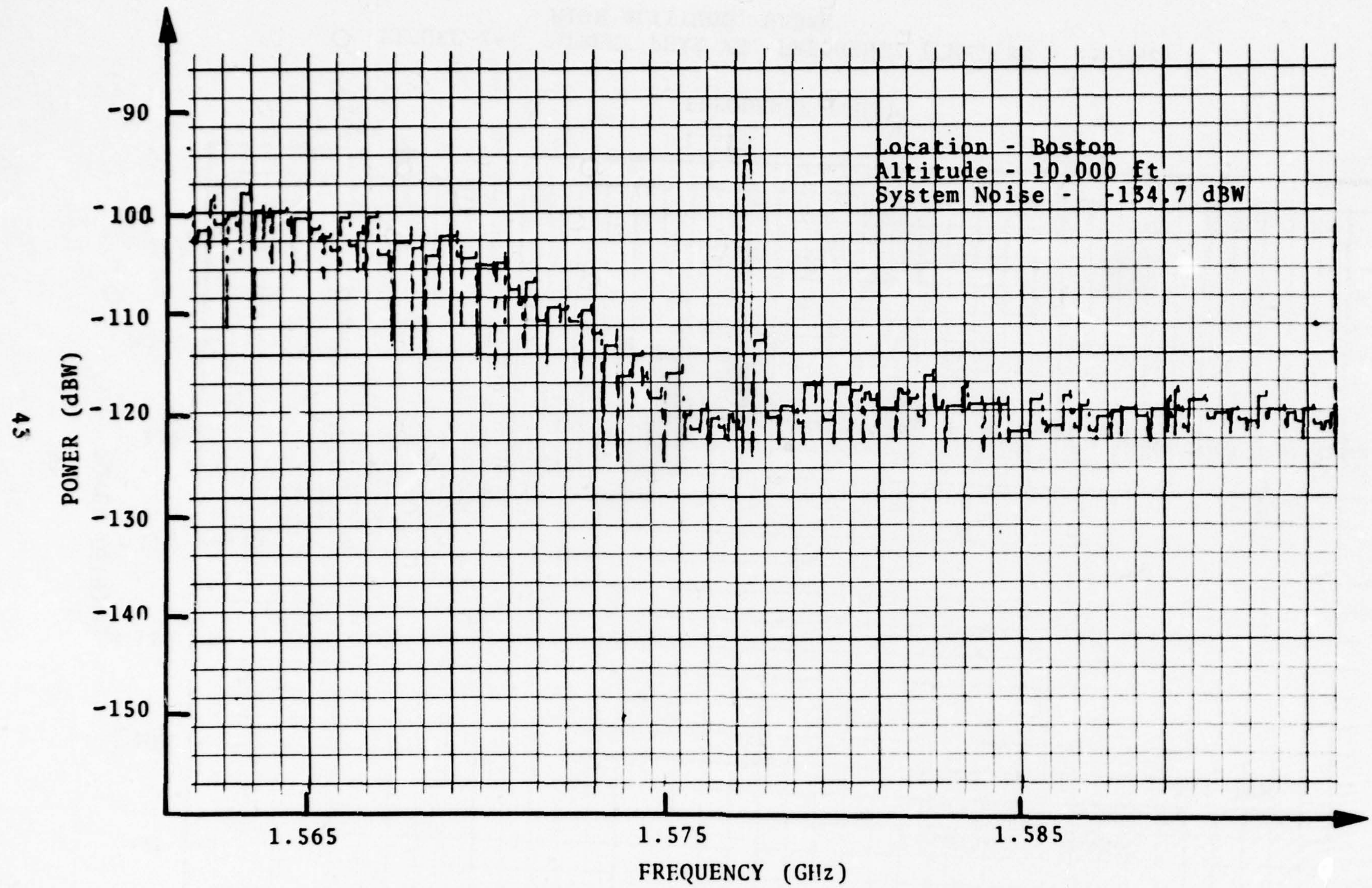

FIGURE 25. DIRECT PEAK VS. FREQUENCY (GHz)(BW = 5 MHz)
HIGH ALTITUDE, URBAN

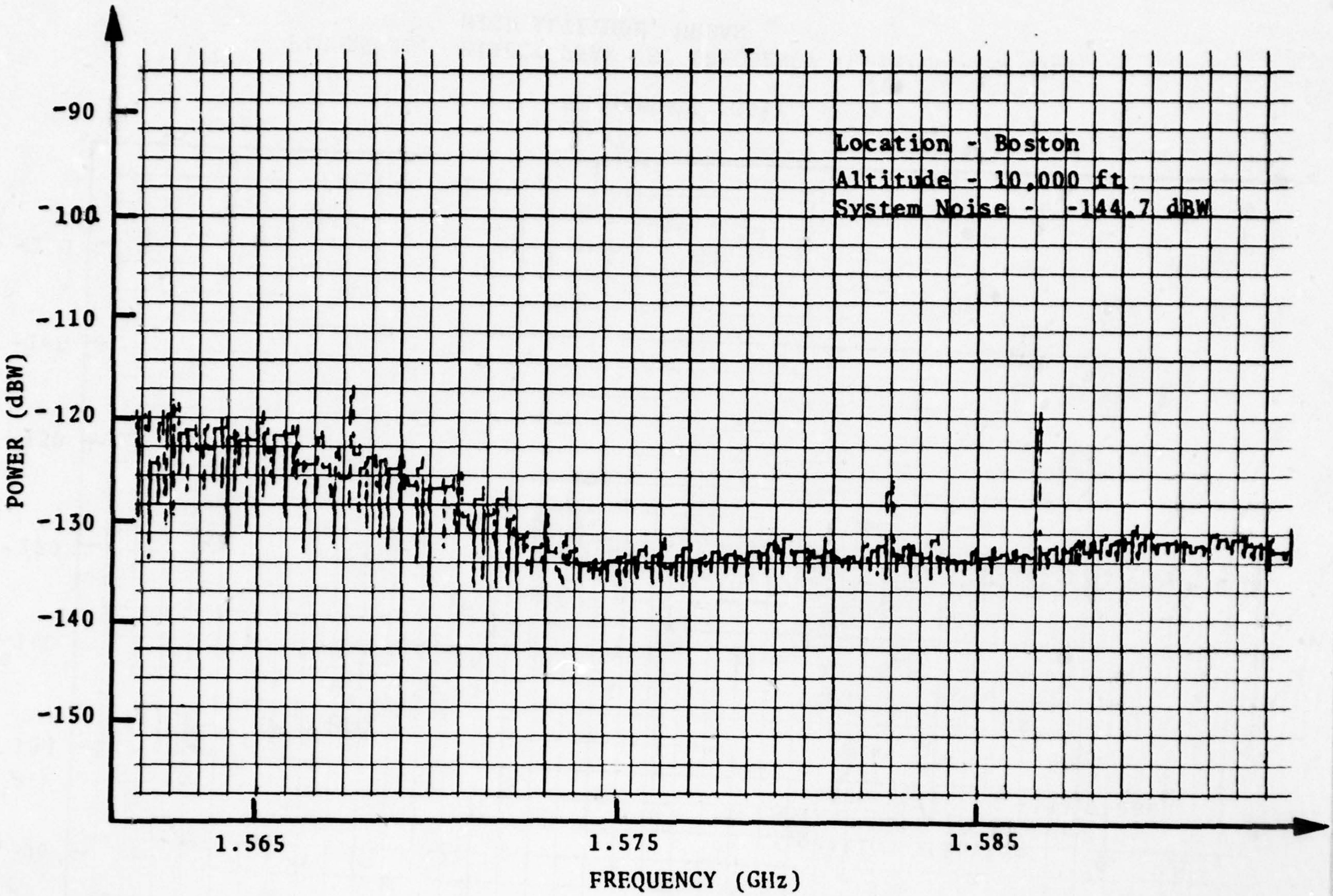

FIGURE 26. DIRECT PEAK VS. FREQUENCY (GHz)(BW = .5 MHz)
HIGH ALTITUDE, URBAN

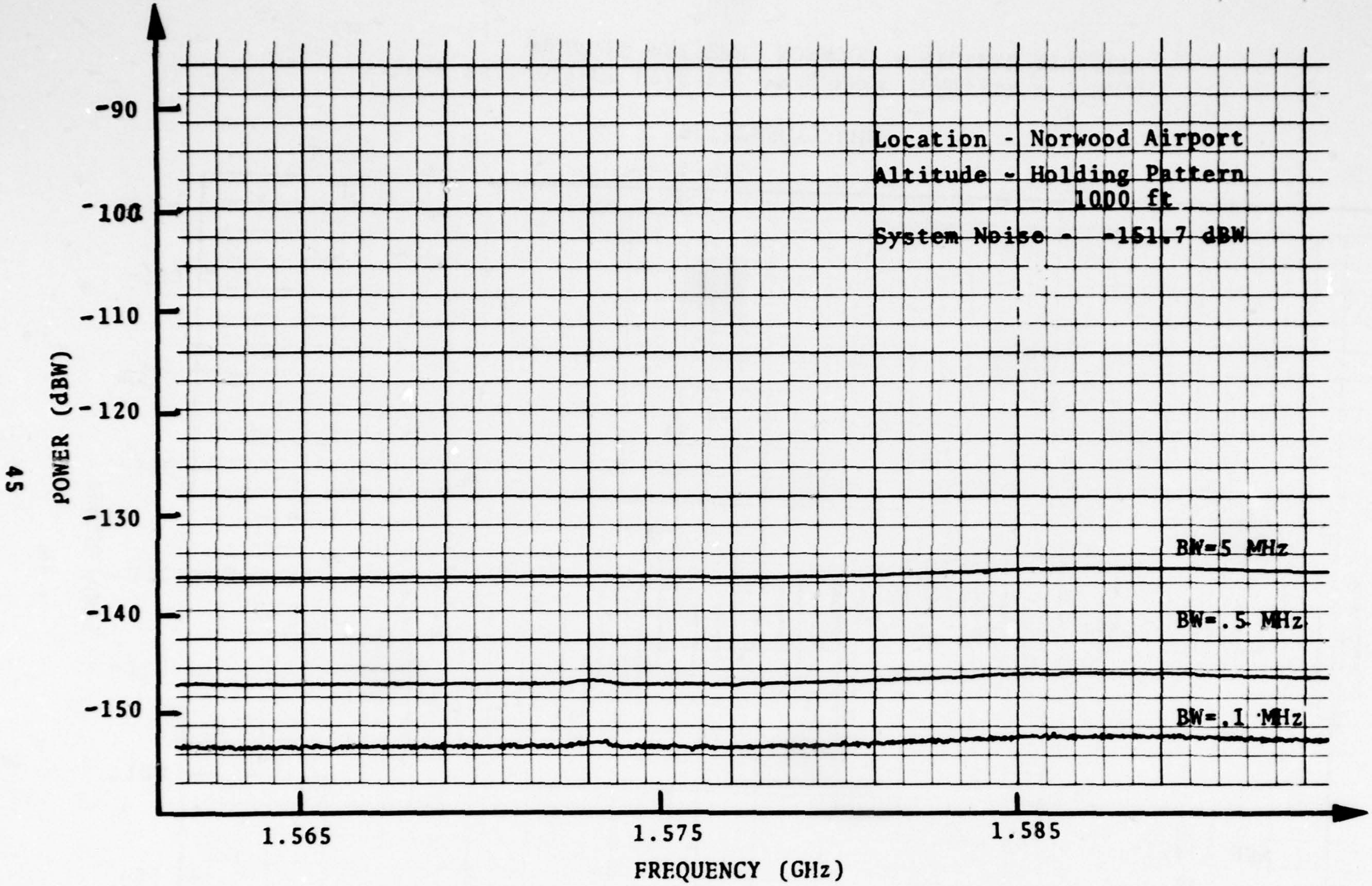

FIGURE 27. FIELD INTENSITY VS. FREQUENCY (GHz)
HOLDING PATTERN, NORWOOD MUNICIPAL AIRPORT

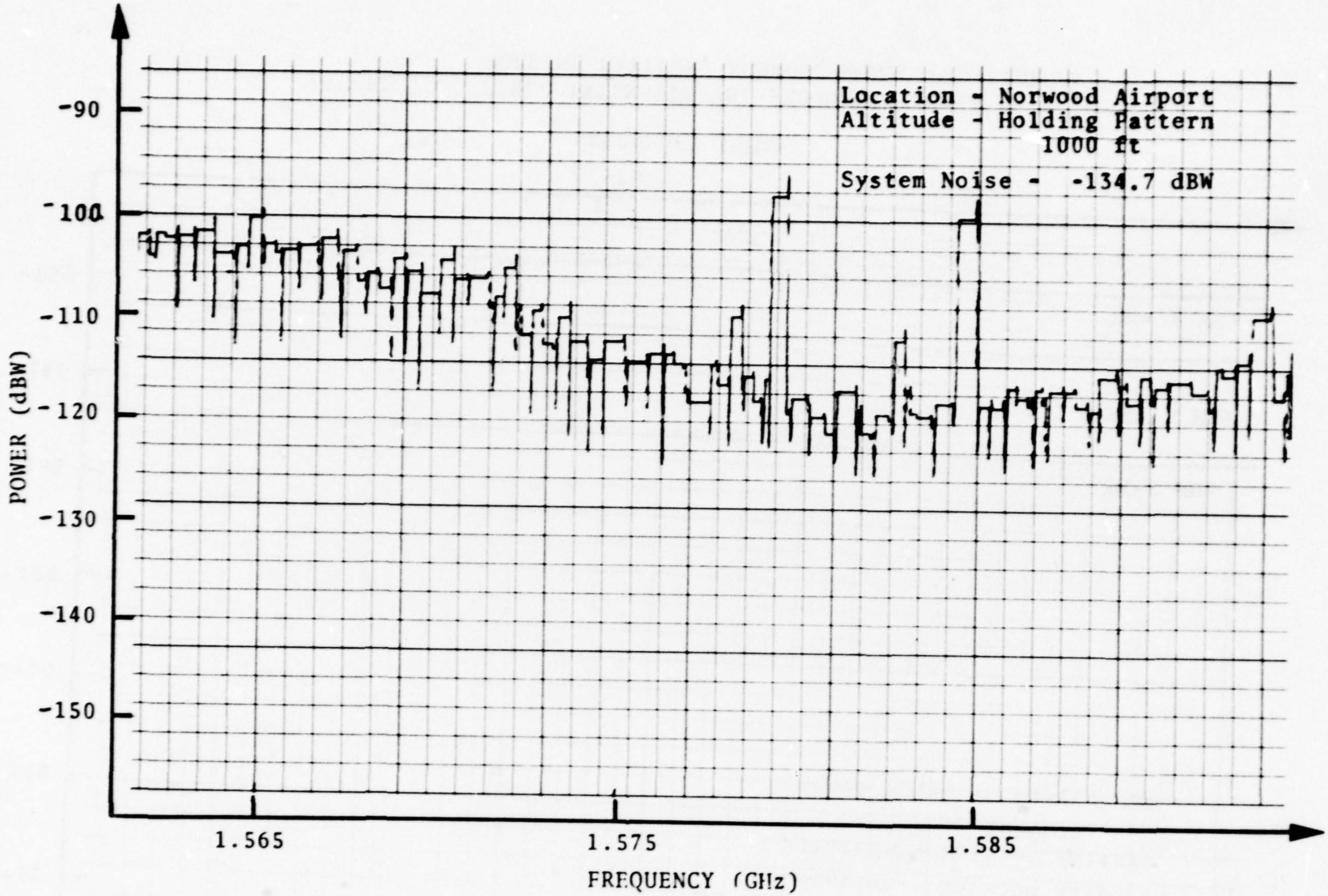

FIGURE 28. DIRECT PEAK VS. FREQUENCY (GHz)(BW = 5 MHz)
HOLDING PATTERN, NORWOOD MUNICIPAL AIRPORT

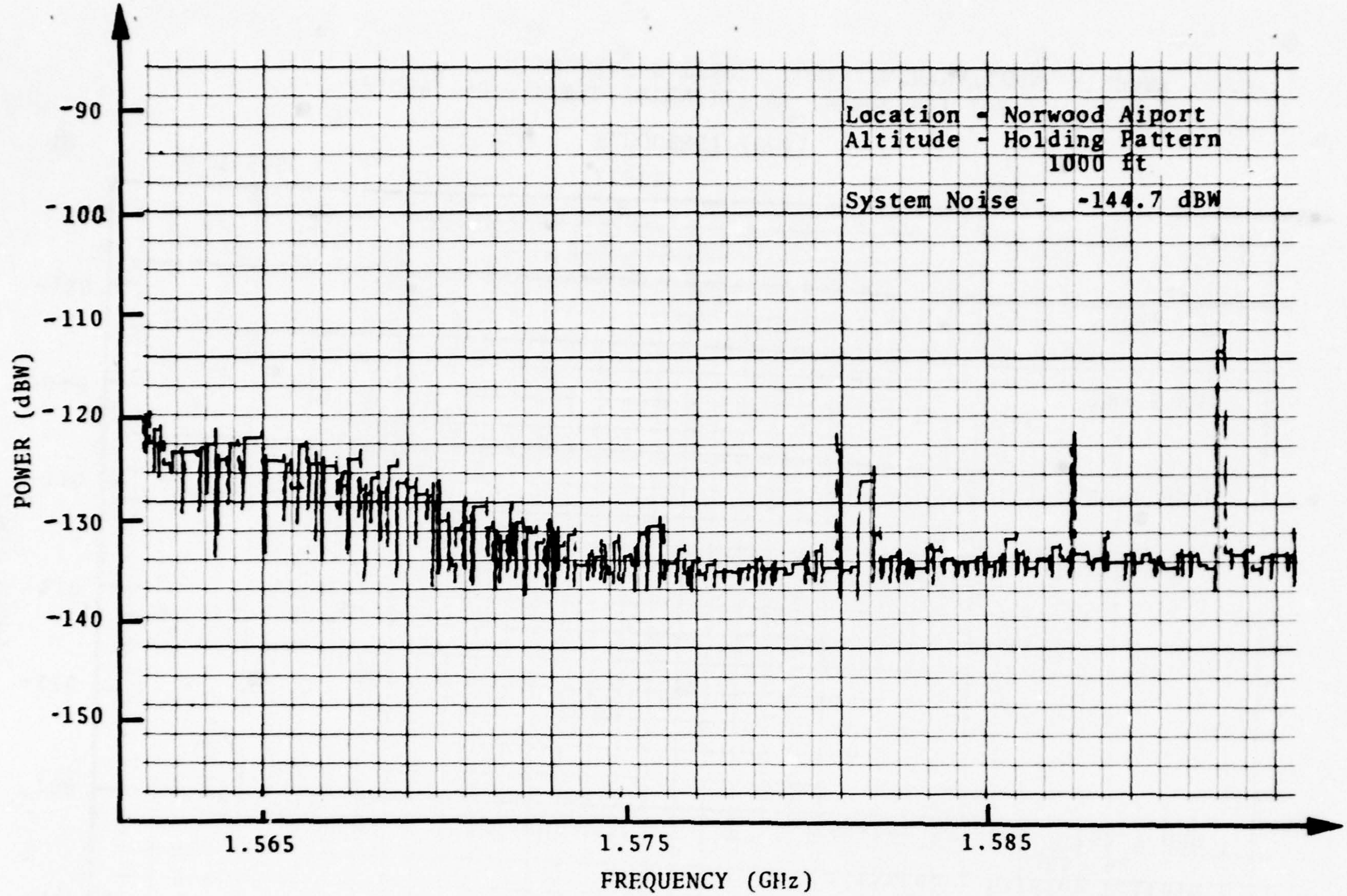

FIGURE 29. DIRECT PEAK VS. FREQUENCY (GHz)(BW = .5 MHz)
HOLDING PATTERN, NORWOOD MUNICIPAL AIRPORT

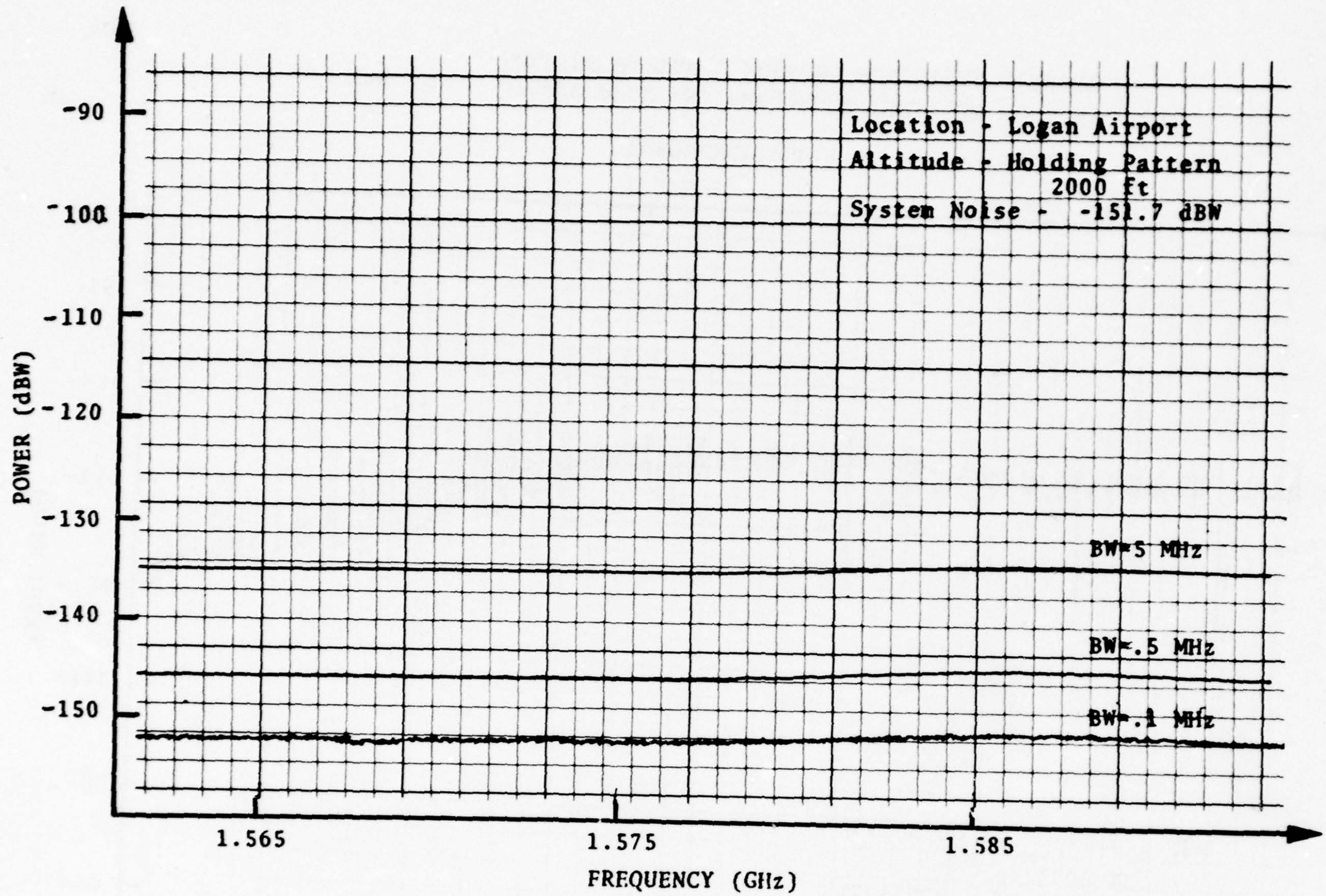

FIGURE 30. FIELD INTENSITY VS. FREQUENCY (GHz)
HOLDING PATTERN, LOGAN INTERNATIONAL AIRPORT

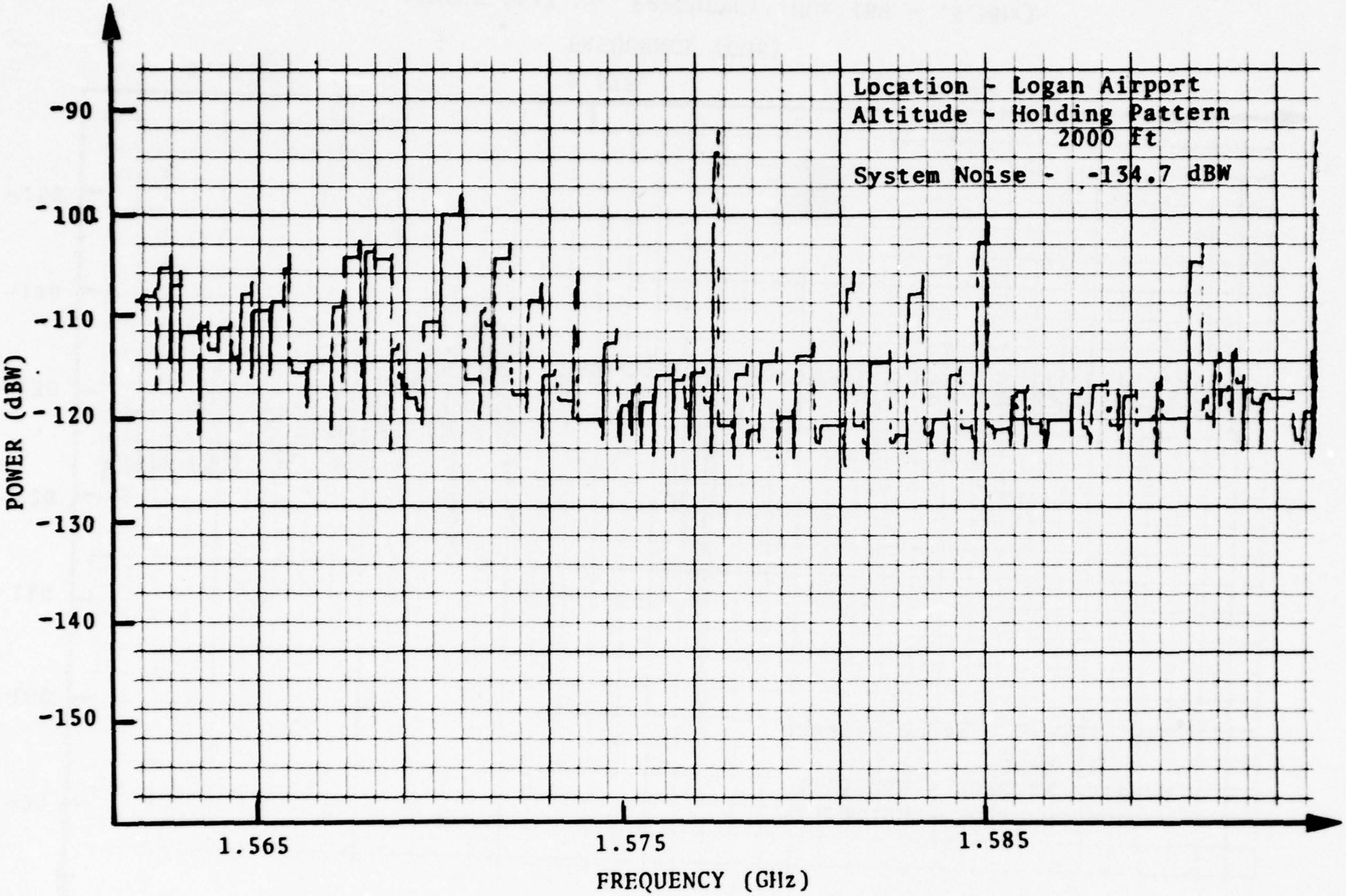

FIGURE 31. DIRECT PEAK VS. FREQUENCY (GHz)(BW = 5 MHz) HOLDING PATTERN, LOGAN INTERNATIONAL AIRPORT

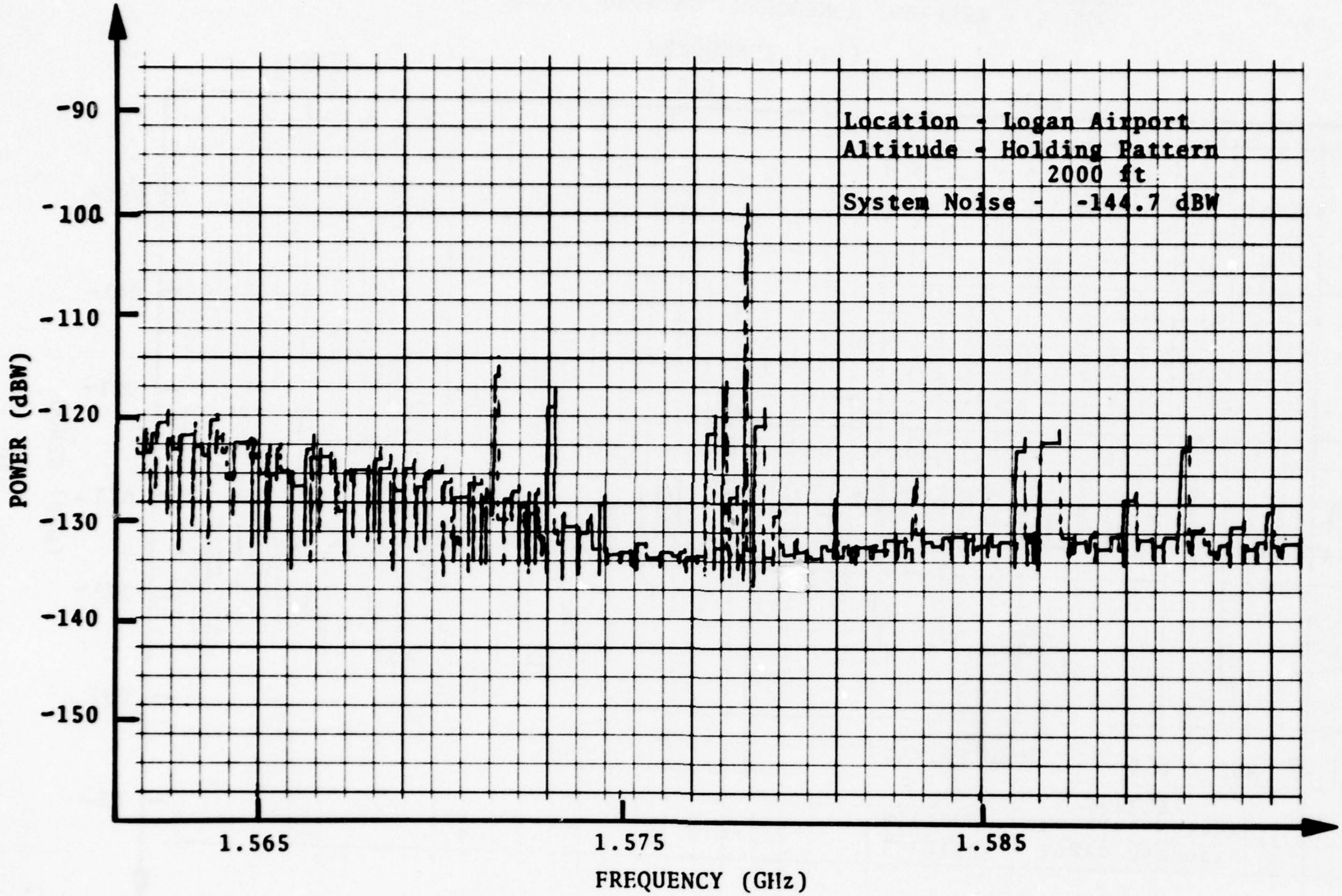

FIGURE 32. DIRECT PEAK VS. FREQUENCY (GHz)(BW = .5 MHz) HOLDING PATTERN, LOGAN INTERNATIONAL AIRPORT

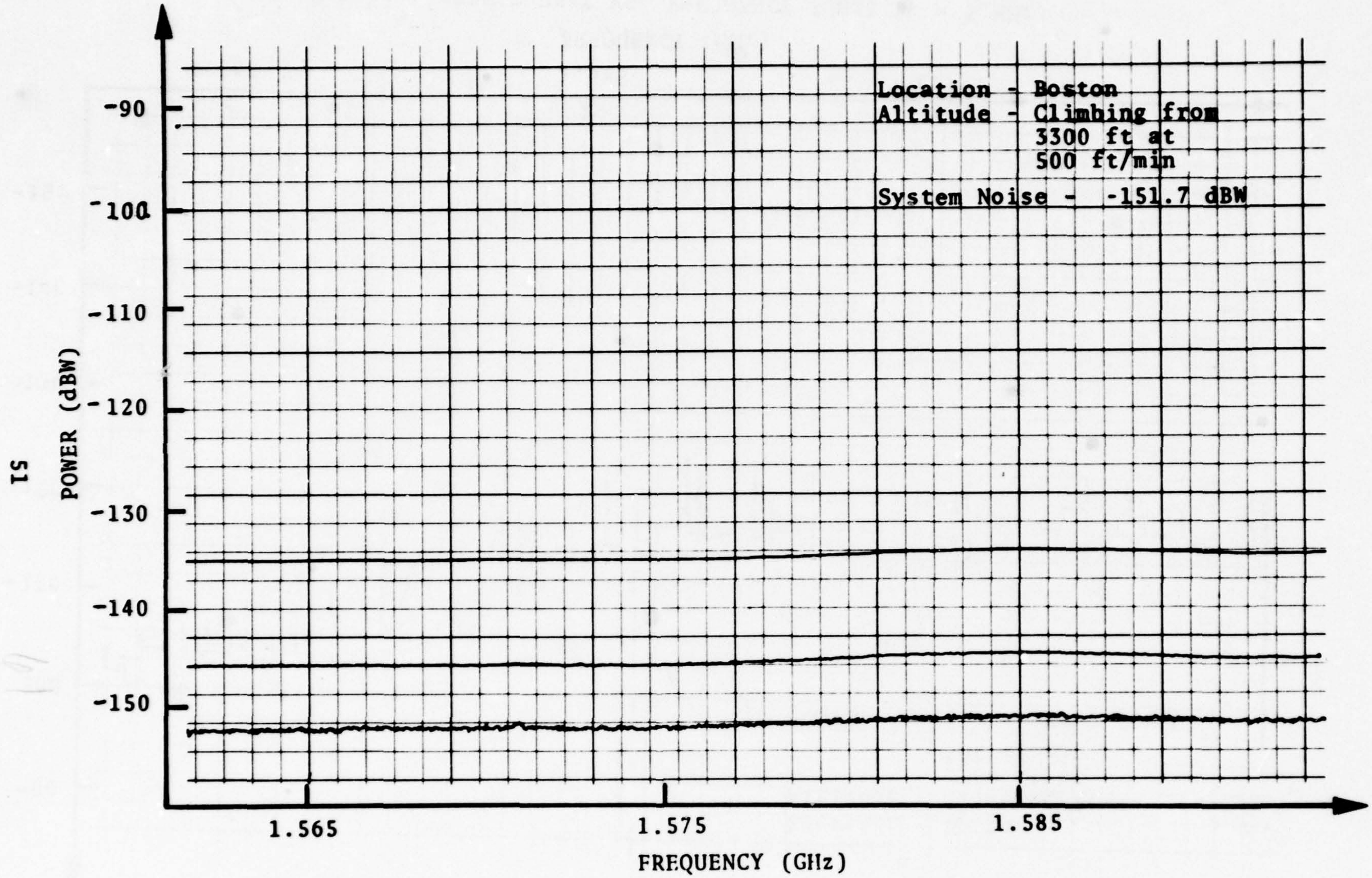

FIGURE 33. FIELD INTENSITY VS. FREQUENCY (GHz) CLIMBING, URBAN

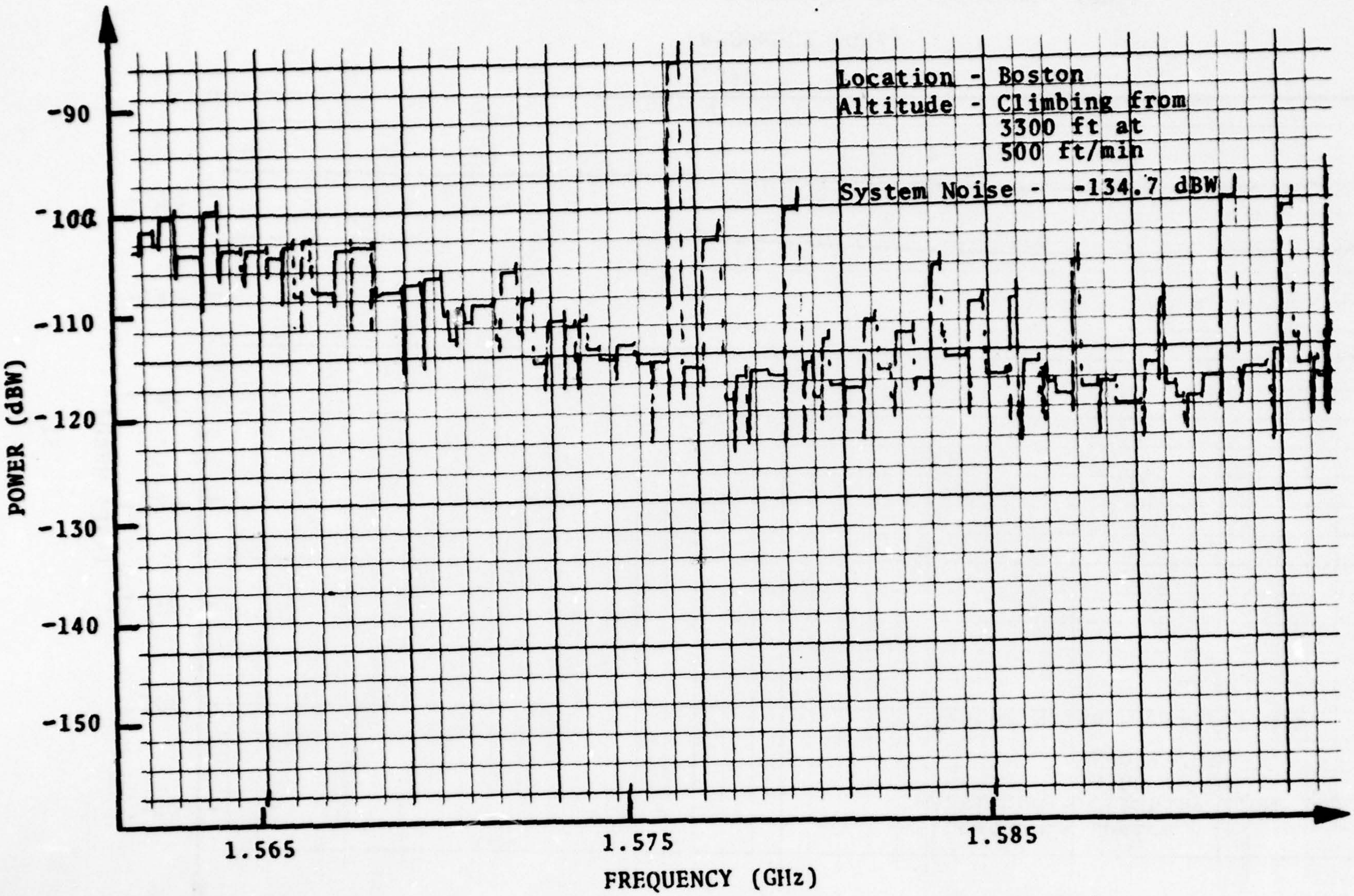

FIGURE 34. DIRECT PEAK VS. FREQUENCY (GHz)(BW = 5 MHz) CLIMBING, URBAN

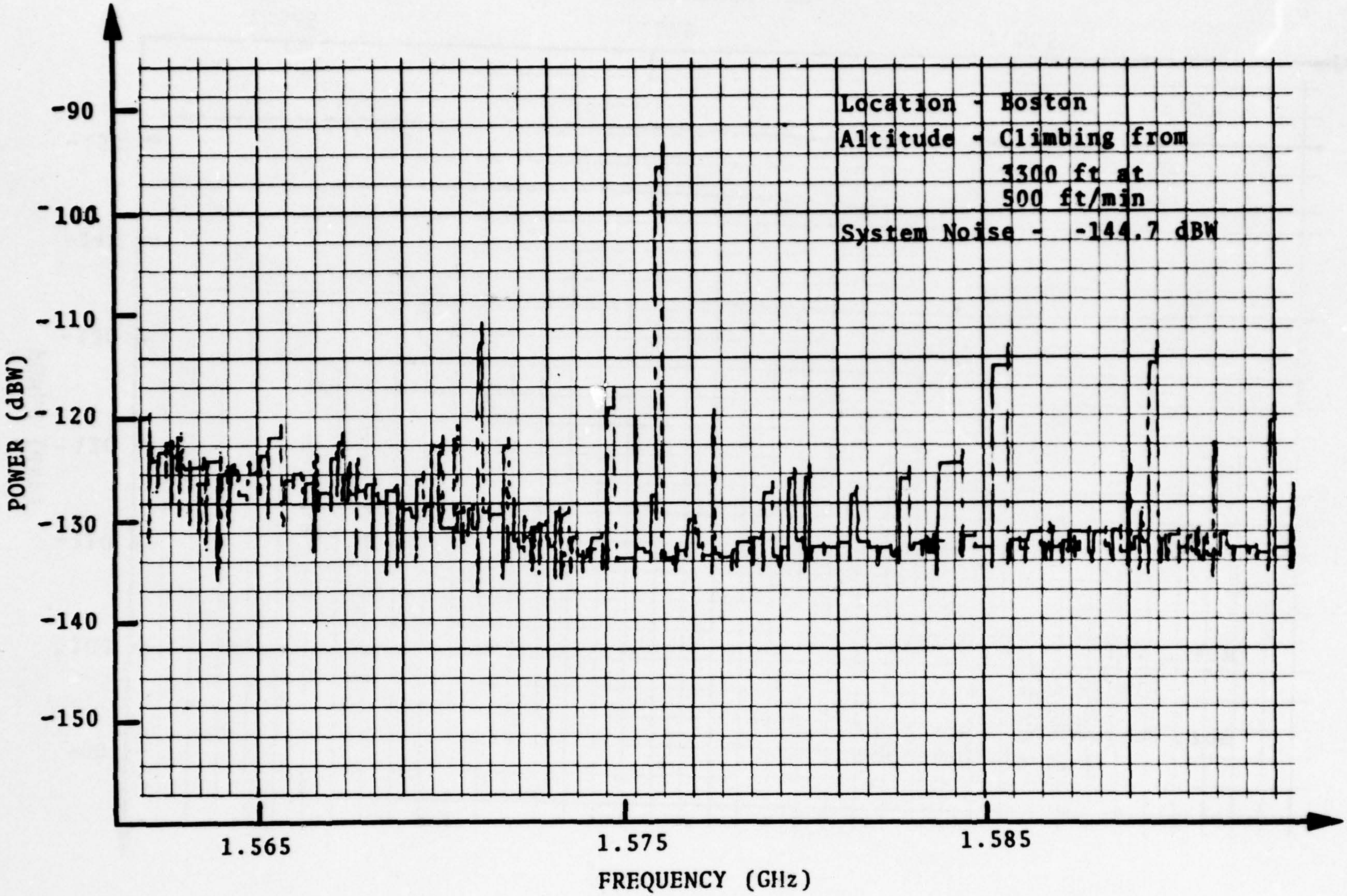

FIGURE 35. DIRECT PEAK VS. FREQUENCY (GHz)(BW = .5 MHz)
CLIMBING, URBAN

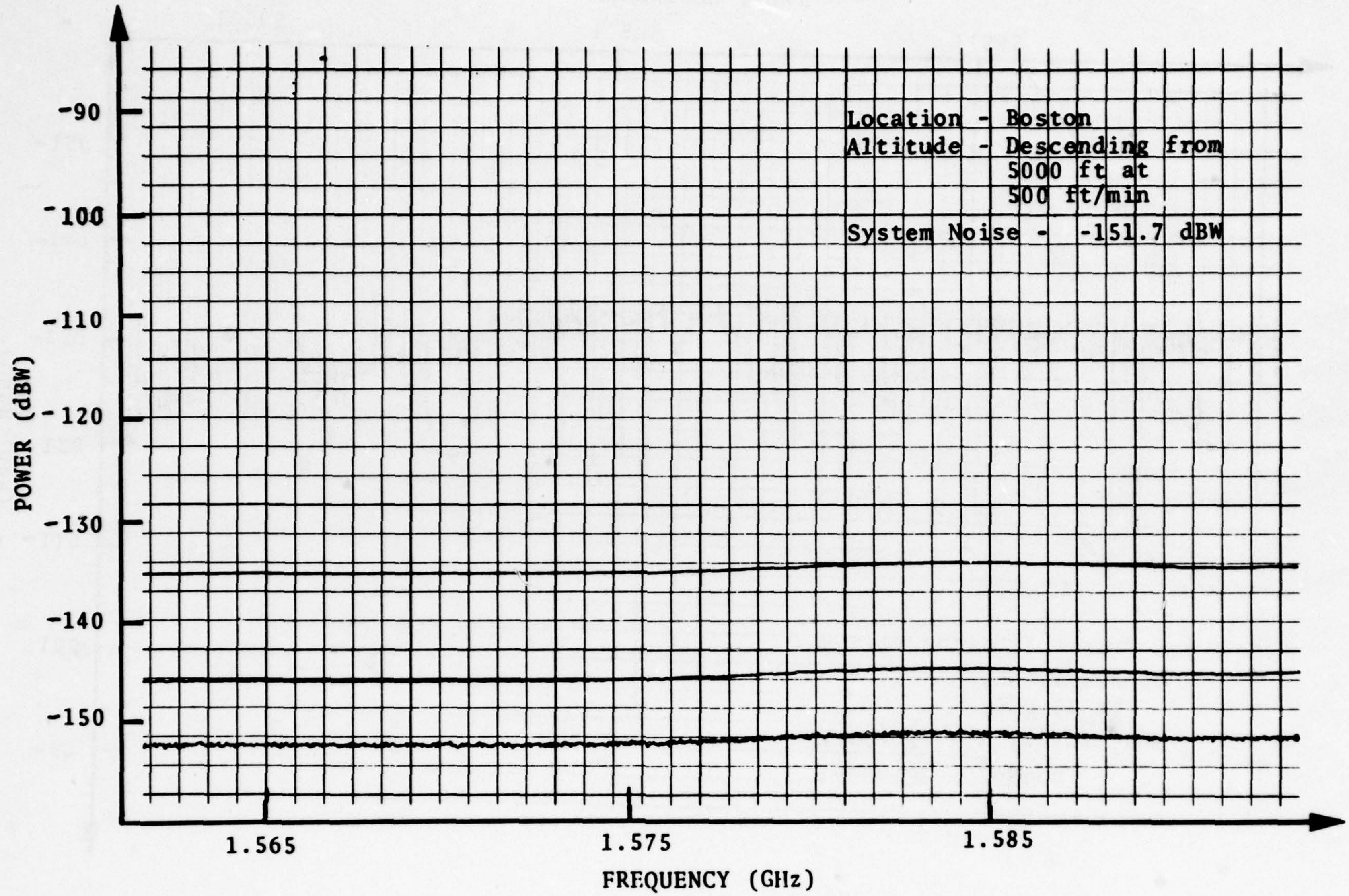

FIGURE 36. FIELD INTENSITY VS. FREQUENCY (GHz)
DESCENDING, URBAN

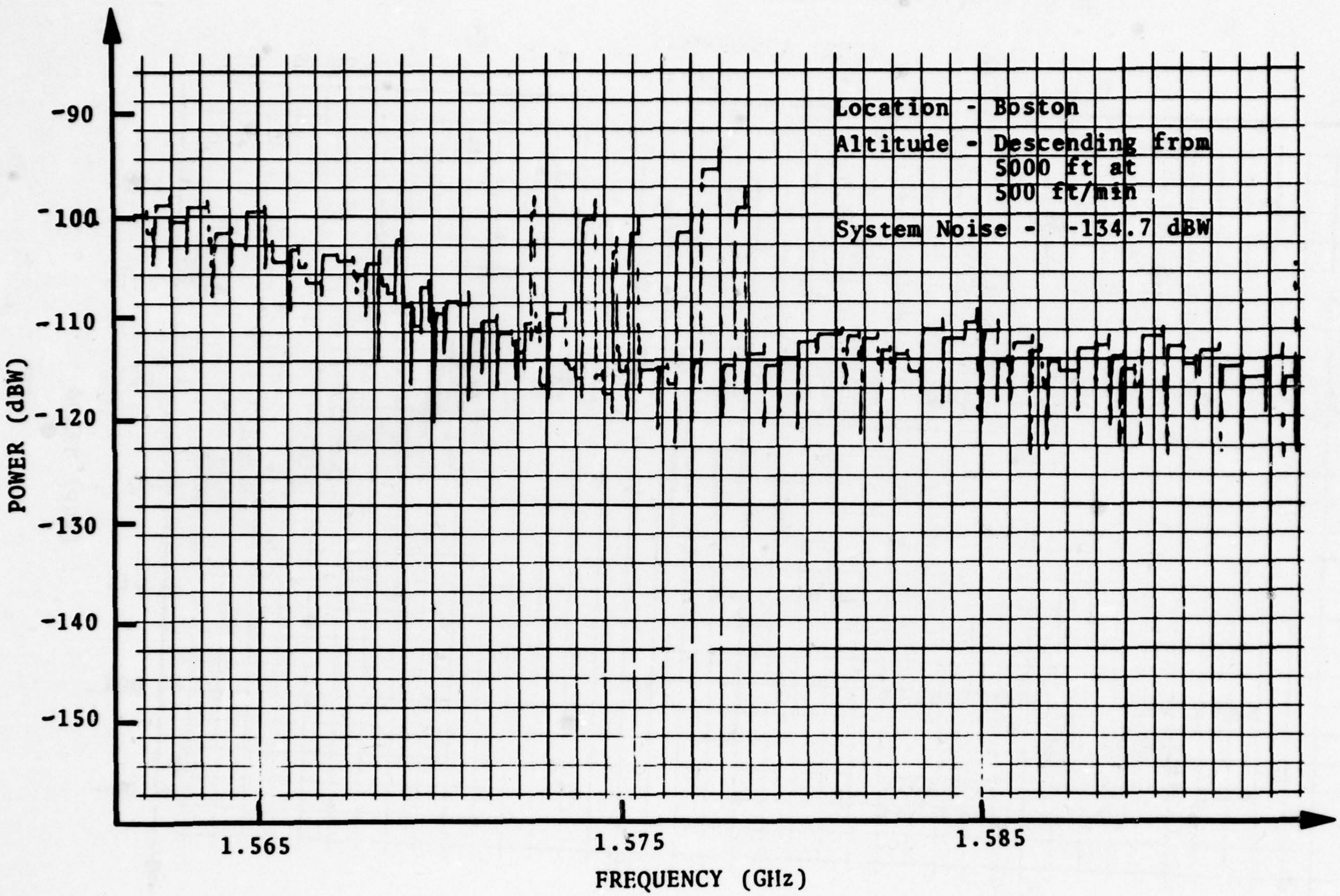

FIGURE 37. DIRECT PEAK VS. FREQUENCY (GHZ)(BW = 5 MHz) DESCENDING, URBAN

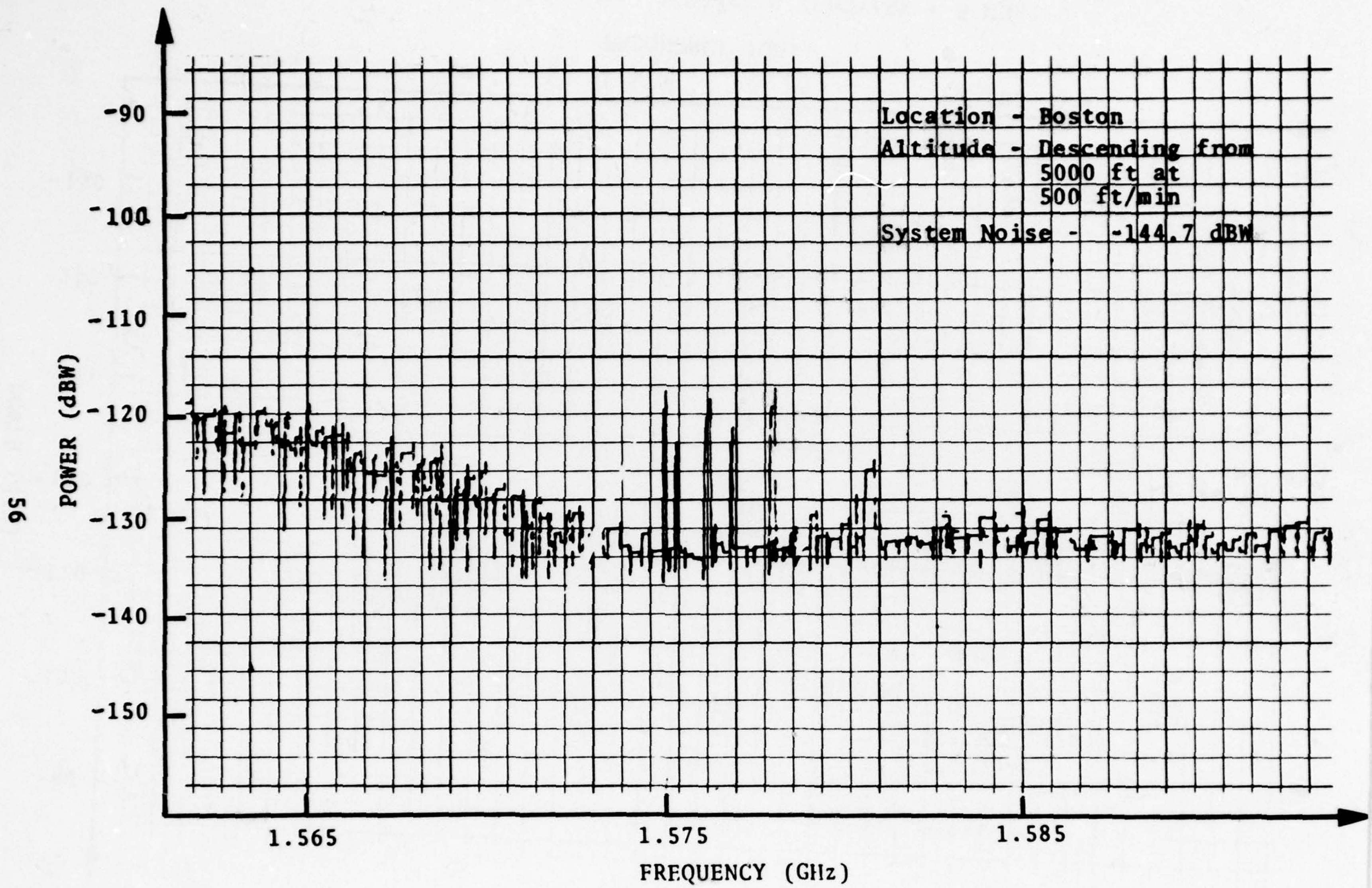

FIGURE 38. DIRECT PEAK VS. FREQUENCY (GHz)(BW = .5 mHz) DESCENDING, URBAN

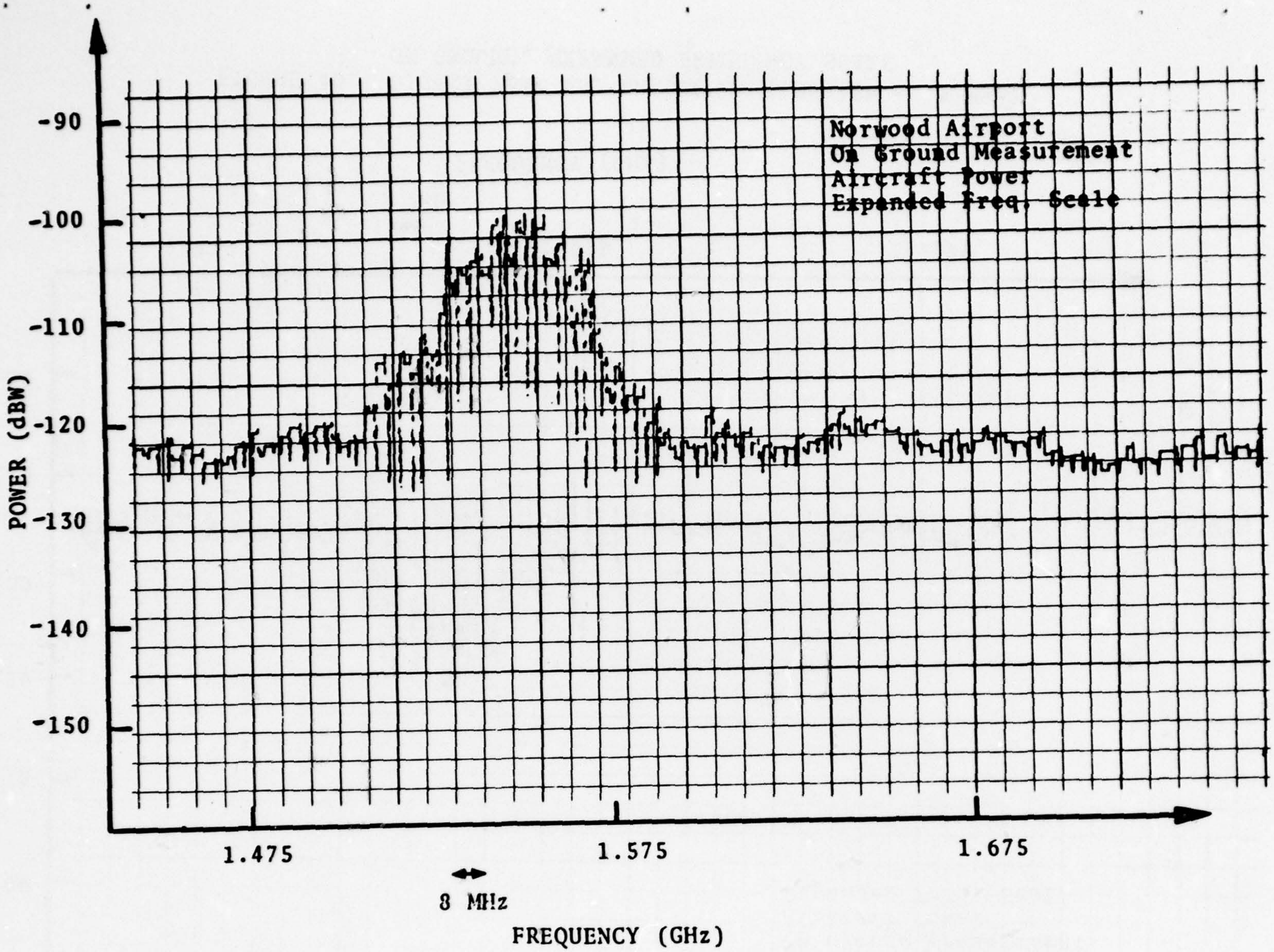

FIGURE 39. DIRECT PEAK VS. FREQUENCY (GHz)(BW = 5 MHz) ON GROUND, EXPANDED FREQUENCY SCALE

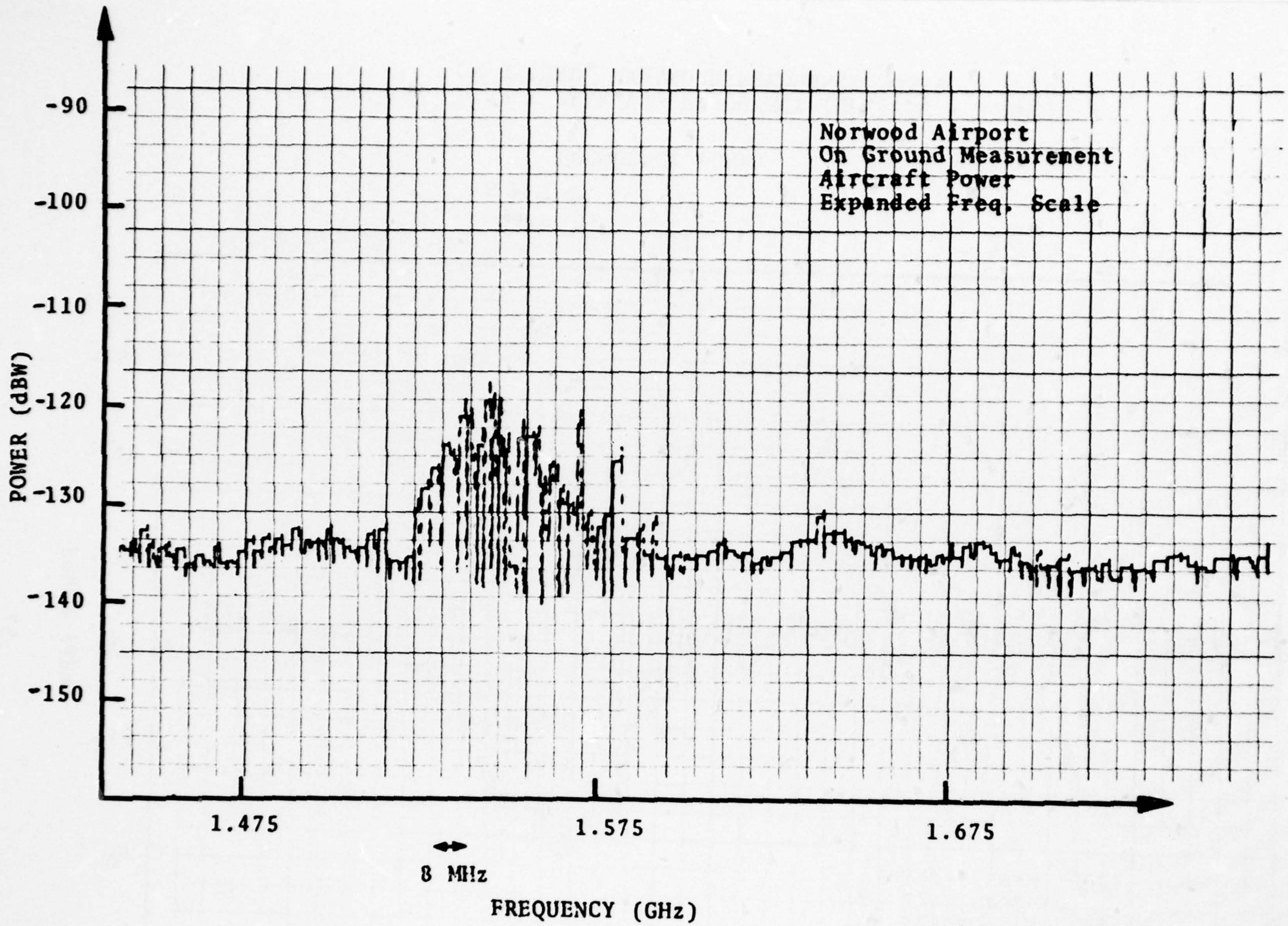

FIGURE 40. DIRECT PEAK VS. FREQUENCY (GHz)(BW = .5 MHz) ON GROUND, EXPANDED FREQUENCY SCALE

7. ANALYSIS OF THE INTERFERENCE POTENTIAL OF U.H.F. TELEVISION IN THE G.P.S. BAND

Although the results presented show no narrowband high power spurious or harmonics present in the G.P.S. L_1 frequency band for a G/A aircraft flying in the Boston area, there is a potential in certain areas for interference from the third harmonic of U.H.F. television transmitters.

The television bandwidth is 6 MHz. The picture carrier, amplitude modulated, lies 1.25 MHz above the lower band edge. The audio carrier, frequency modulated, lies 4.5 MHz above the visual carrier, and there is the chromatic subcarrier at 3.6 MHz above the visual carrier. See Reference 1. Most of the power lies in the visual and audio signals with a lesser amount in the chromatic subcarrier. Calculation of the third harmonic of the visual carrier of U.H.F. television station Channel 23, (524MHz to 530MHz), shows its frequency to be 1575.75 MHz, 330 KHz from the G.P.S. center frequency and well within the bandwidth of the G.P.S. C/A signal.

U.H.F. television stations (channels 14-83) are restricted to a maximum power output of 5000 kilowatts. FCC regulations require the third harmonics of the transmitter output to be at least 60dB below the fundamental (Ref. 3). Thus for a station radiating at maximum power output, 5000 KW (+67 dBW), the power in its third harmonic would be +7dBW, and thus the power level of the visual carrier is +4dBW on the assumption that half the power is in the visual carrier, an assumption supported by examination of the spectrum of a TV signal. Allowing 2.2dB further loss due to antenna rejection of the third harmonic yields an effective radiated power of of +1.8dBW*. Free space attenuation is given by:

$$\alpha_{dB} = 36.6 + 20 \log f + 20 \log d \qquad (5)$$

where f is in MHz and d is in miles.

The power level as a function of distance can be calculated. The results are shown in Table 3.

*The basis of this statement is a measurement carried out for TSC by Chu Associates of Littleton, Mass. A calibrated UHF dipole was excited at its 3rd harmonic and showed a VSWR of about 4.5. This is equivalent to a transmission loss of 2.2dB. Actual TV transmitters may show greater 3rd harmonic attenuation.

TABLE 3. POWER OF THE 3RD HARMONIC VS. DISTANCE FROM THE TRANSMITTER

Distance (miles)	Signal Level (dBW)
1	-98.8
2	-104.8
5	-112.8
10	-118.8
20	-124.8
50	-132.8
100	-138.8
200	-144.8

Next, the G.P.S. spread spectrum receiver can tolerate narrowband interference because it spreads the interference over 2MHZ, the bandwidth of the C/A signal. Since

$$C/N_{o\,eff} = \frac{C_o/N_o}{1 + \frac{P_I}{R_c N_o}}, \qquad (6)$$

with R_c = 1 MHz, a P_I (interference signal level) of 60dB above N_o will cause only a 3dB degradation in C/N_o. See Reference 4. Thus, with N_o = -200 dBW/Hz, -140dBW is the interfering signal level that will cause a 3dB degradation in C/N_o. From Figure 5, it is seen that the antenna pattern will offer further rejection of the unwanted signal which will be a function of aircraft altitude and distance from the television station. Table 4 lists the interference power level at the receiver.

TABLE 4. POWER OF INTERFERENCE AT RECEIVER INPUT AS A FUNCTION OF ALTITUDE AND DISTANCE

Alt (miles)	D (miles)	INTERFERENCE POWER at the RECEIVER (dBW)
.5	1	-114.6
1	1	-121.8
2	1	-135.6
.5	2	-119.2
1	2	-120.6
2	2	-124.8
.5	5	-122.8
1	5	-125.9
2	5	-128.3
.5	10	-127.8
1	10	-128.8
2	10	-131.8
.5	20	-132.8
1	20	-133.8
2	20	-134.8
.5	50	-140.8
1	50	-140.8
2	50	-141.8

From Table 4, it is evident that the received C/N_0, a function of satellite position, begins to degrade when the aircraft is 30 to 40 miles from the interference transmitter in this worst case analysis. It is also seen that a higher altitude offers more interference rejection for two reasons: 1) greater distance between the aircraft and the transmitter 2) discrimination against interference by both TV and aircraft antenna patterns. See Figure 41.

The above analysis assumes maximum T.V. transmitter power, minimum filtering of the third harmonic, minimum antenna rejection of the third harmonic, and the G.P.S. antenna pattern of Figure 5. Should the station output be less than maximum as are station locations within 250 miles of the Canadian border, for example, where the output is restricted to 1000KW, and should the third harmonic be down 70dB from the fundamental, and should the transmitting antenna rejection of the third harmonic be greater than 2.2dB, an improvement of 20dB would be possible, virtually eliminating any interference problem except when the aircraft is operating close to the transmitter (i.e. $<$ 1 mile at low altitude).

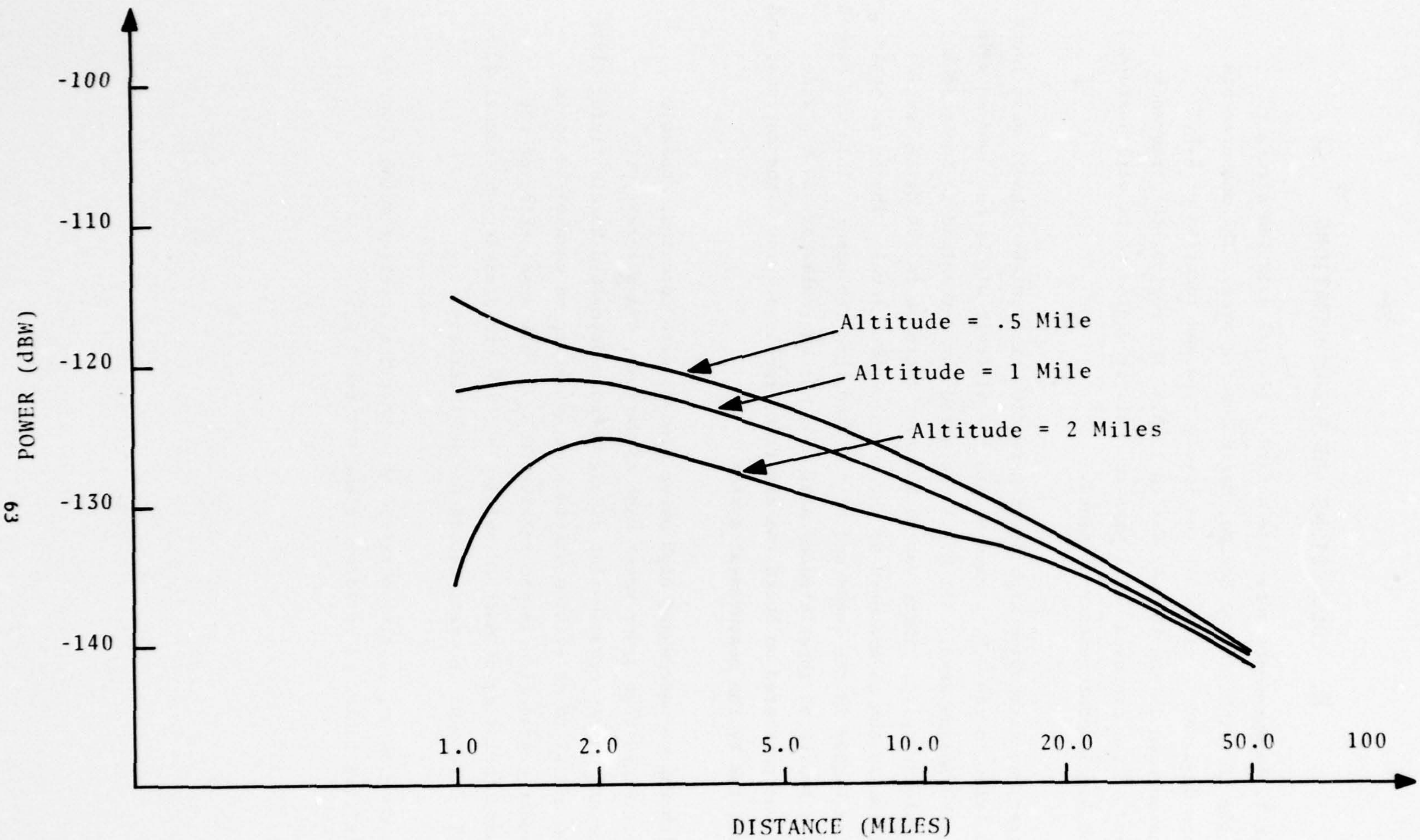

FIGURE 41. INTERFERENCE EFFECT OF THE THIRD HARMONIC OF U.H.F TELEVISION CHANNEL 23 ON THE RECEPTION OF THE C/A SIGNAL ON L_1 OF THE G.P.S. AS A FUNCTION OF AIRCRAFT DISTANCE AND ALTITUDE

8. CONCLUSIONS AND RECOMMENDATIONS

R.F.I. measurements were made aboard a general aviation aircraft while in flight in the Boston, Massachusetts area. The measurements were designed to establish the level, type and location of R.F.I. encountered in the 1565.42 MHz to 1585.42 MHz region, the frequency band of the proposed G.P.S. system. All scheduled tests were performed and significant results obtained.

First, no narrowband high power harmonics or spurious signals were found to exist in the G.P.S. band aboard the aircraft within one hundred miles of the Boston area. All R.F.I. detected was determined to be broadband impulsive noise. There was no observed increase in the noise level of the system as measured by the average power level. The noise peaks were higher in the lower end of the band than the upper. This was caused by a source of interferences near 1551 MHz approximately 20 MHz wide. It was generated on board the aircraft, received through the antenna, and detected by the measurement system.

Although no narrowband high power signals were detected, analysis determined that under worst case conditions, G/A aircraft with the microstrip crossed-slot dipole antenna described herein flying close (40 miles) to television stations broadcasting on channel 23 could expect degradation in the received C/N_o. Only examination of the characteristics of each television station broadcasting on Channel 23 will determine the real nature of any interference.

In conclusion, results obtained show that the receiver noise floor is the limiting factor of performance and not the R.F.I.

9. REFERENCES

1. Westman, H.P., Reference Data for Radio Engineers, Fifth Edition, Howard W. Sams, Indianapolis, 1972.

2. World Distribution and Characteristics of Atmospheric Radio Noise, C.C.R. Report 322, Tenth Plenary Assembly, Geneva, 1963.

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